G.E.C. Journal

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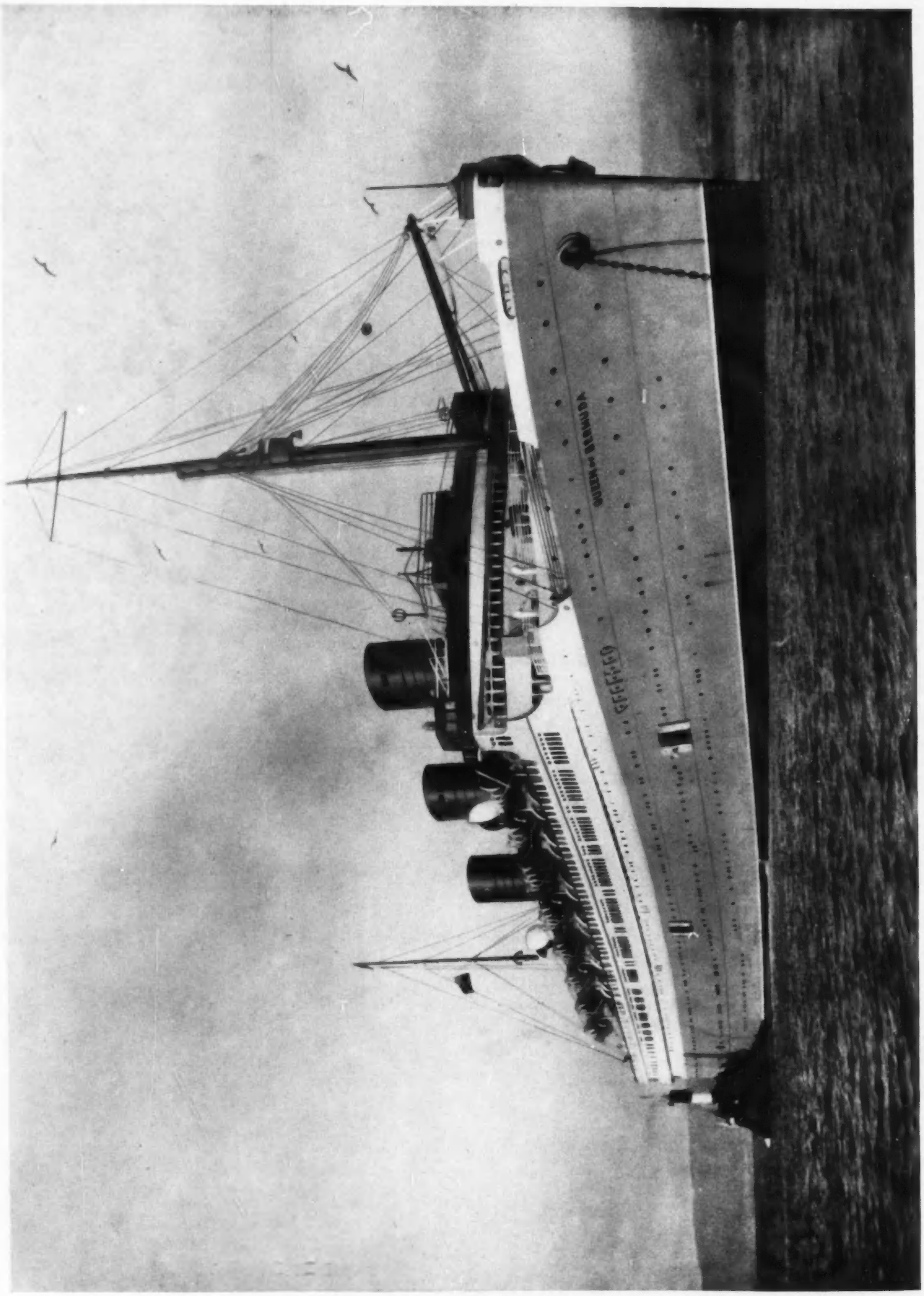

Q.T.E.V. *QUEEN OF BERMUDA.*

A complete description of the electrification of this liner carried out by The General Electric Co., Ltd., is given on page 116.

G.E.C. Journal

VOL. IV. MAY, 1933. No. 2.

Metalclad Switchgear at Sheffield.

The first part of this description, dealing with the main 11,000 - volt, compressed - air operated metalclad switchboard supplied to Sheffield Corporation, is reprinted by kind permission of the proprietors of "Engineering," and was first published in the issue of that journal dated April 7th, 1933.

A brief outline of the auxiliary switchgear, comprising the two auxiliary switchboards, the control board and the reactors, has been added, as they form an important part of the complete installation.

ONE of the most comprehensive installations of metalclad switchgear is that at the Blackburn Meadows No. 2 Generating Station of Sheffield Corporation, which was officially opened on the 6th April, 1933. The equipment comprises a main 11,000 volt switchboard, an 11,000 volt works auxiliary board, and a works L.T. board, all of which are of the metalclad type; also a control board for the main switchboard, battery charging equipment and concrete type reactors for insertion in outgoing feeders. The whole of this equipment was manufactured and supplied by The General Electric Co., Ltd.

MAIN 11,000-VOLT METALCLAD SWITCHBOARD.

Although the main switchgear complies generally with British standard practice, it also incorporates a number of unusual features. In the first place, compressed air, instead of solenoids or motors, is used to close the circuit-breakers and the latter, together with their hoisting and lowering gear, duplicate busbar chambers, current and potential transformers, interlocks and other equipment, are erected on a framework with a central gangway, an arrangement which has enabled floor space to be saved, and accessibility to be increased. The hoisting and lowering gear, which is of novel design, is operated by a self-contained motor, and is so arranged that the circuit-breaker can be isolated and the tank lowered without the use of auxiliary apparatus. Anti-friction bearings are employed throughout the equipment, and all the important bolts and nuts on the circuit-breakers are made of high-grade stainless steel, this material having been found more even in quality than the non-alloyed product. Any feeder and, if necessary, any busbar, can be expeditiously and safely earthed through its associated circuit-breaker. The busbars are of tubular form, and are housed in chambers made of non-magnetic alloy and filled with compound. The isolating contacts are specially arranged, so that the resistance at this point is a minimum.

General views of the equipment installed in the station are given in figs. 1, 2 and 3, while the details of its construction will be appreciated from figs. 4, 5, 6 and 7. As will be seen, there is a rolled steel frame on which the equipment is mounted so as to leave a central passage between the two rows of circuit-breakers below the busbars. Over this passage is a gangway, which is shown in fig. 3, giving access to platforms, from which the potential transformer gear can be operated and the inspection, oiling, and general maintenance of the apparatus carried out. The framework is divided by its supporting stanchions into ten bays, and each bay contains an oil circuit-breaker, together with its operating and hoisting gear, protective equipment and interlocks. One of these breakers controls a 31,250 kVA alternator, and the others are for the feeders which run either to the adjacent Central Electricity Board sub-station, or are used for local supply purposes. In addition, the front and rear busbars contain a bus coupler and bus sectioning switch respectively. The operating pressure of the board is

11,000 volts, while the rupturing capacity of each breaker is 1,500,000 kVA.

The construction of the circuit-breakers used in this equipment will be clear from an examination of figs. 8 and 9. It will be seen that they embody a common top plate, from which the operating mechanism is suspended, and on which the condenser-type terminals are mounted. This top plate is formed by rolling a steel ingot down to a thickness of 4 in., an additional ½ in. of material being subsequently removed by machining. Prior to the latter operation, however, portions of the plate are cut away by an oxy-hydrogen flame, so that three holes, with clean edges, are obtained, and these are filled with plates of non-magnetic material, in order to reduce the hysteresis losses caused by the flow of current through the connections. The bakelite condenser bushings, which support the fixed contacts, have a shrunk-on centre flange, which is bolted to the underside of these plates, as shown in fig. 10, and their lower portions are shrouded by a compound filled porcelain shield, which is so arranged that any ingress of oil from the tank is prevented. This shield insures against the surface of the bushing being carbonised by the hot gases generated when the circuit is opened. The fixed contacts themselves, which are also visible in fig. 10, are of the controller finger pattern and are arranged in pairs. They consist of a hard-drawn copper section with a rounded face, which is riveted to a number of thin copper laminations, the latter being backed by a steel spring. On the other hand, the main moving contacts, which can be seen in the same illustration, consist of copper bars of wedge section, the number depending on the current the switch is designed to carry. It is considered that the combination of this wedge section with the rounded face of the fingers on the fixed contacts ensures that a self-cleaning surface is obtained, a point of importance when the breakers have operated on overload. Moreover, tests have shown that the current-carrying capacity of contacts of this form is superior to that of any type of flat faced contact of the same size. It may also be noted that as the fingers are arranged in pairs, the pressure between them is increased by the electromagnetic attraction during overloads and there is no risk, therefore, of arcing or welding occurring. The arcing contacts are of the same shape as the main contacts, but are of much heavier section. They are also arranged in pairs, and are carried on hollow porcelain posts which are filled with oil from the tank. Altogether, therefore, there are two main and four auxiliary breaks on each phase, the length of each auxiliary break being 15 in. The bars carrying the main moving contacts and the arcing contacts are clamped to girder-shaped cibanite beams by stainless steel bolts, the latter being locked in place by plates. At each end of these beams is a nut which engages with a vertical screw, the latter being, in turn, connected to the operating mechanism as described below. It may be mentioned that

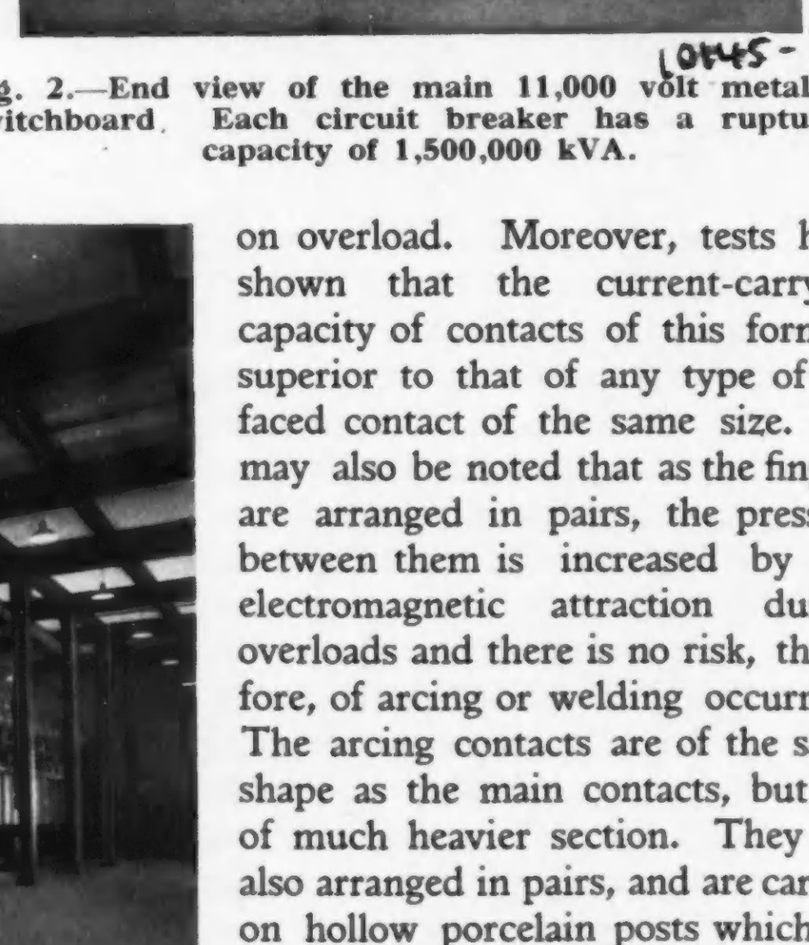

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Fig. 2.—End view of the main 11,000 volt metalclad switchboard. Each circuit breaker has a rupturing capacity of 1,500,000 kVA.

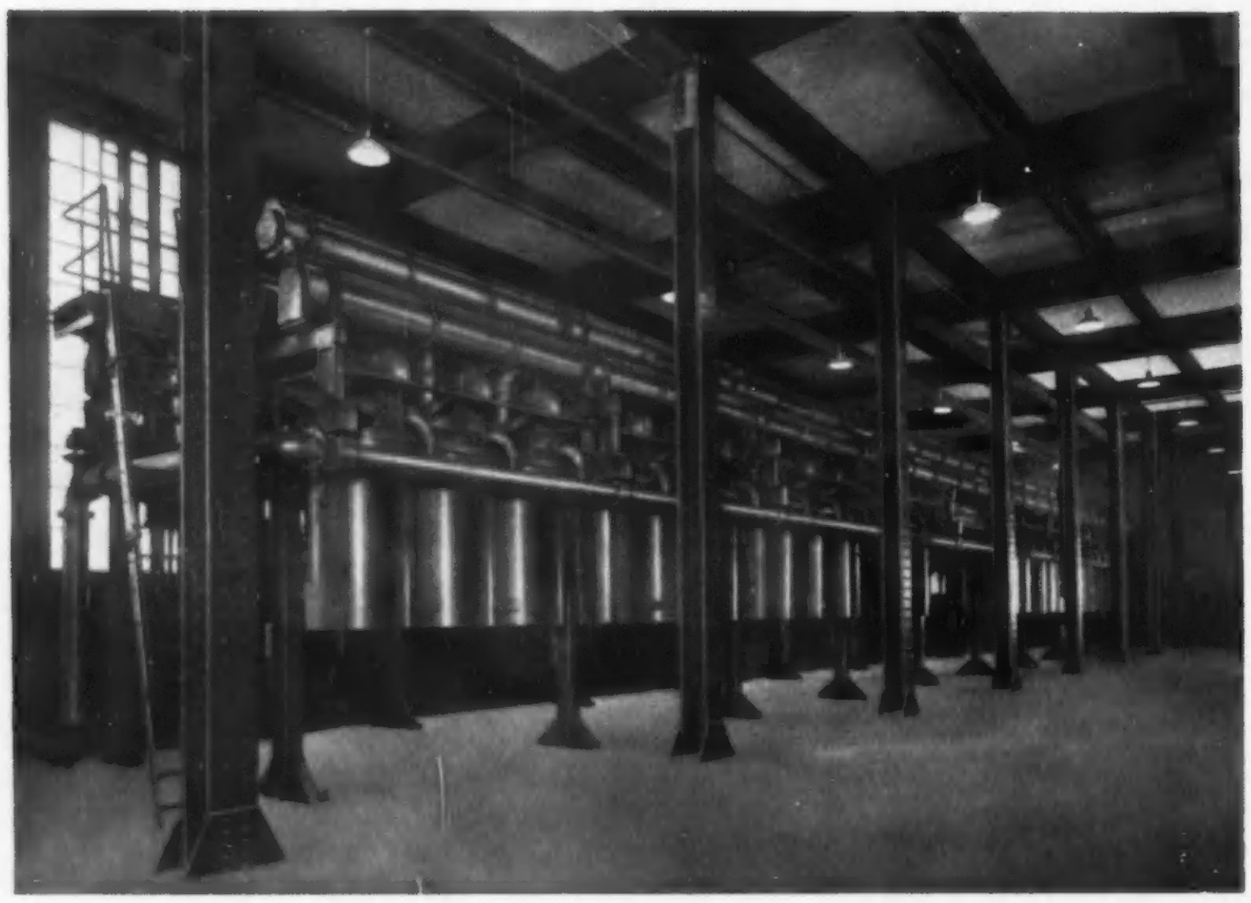

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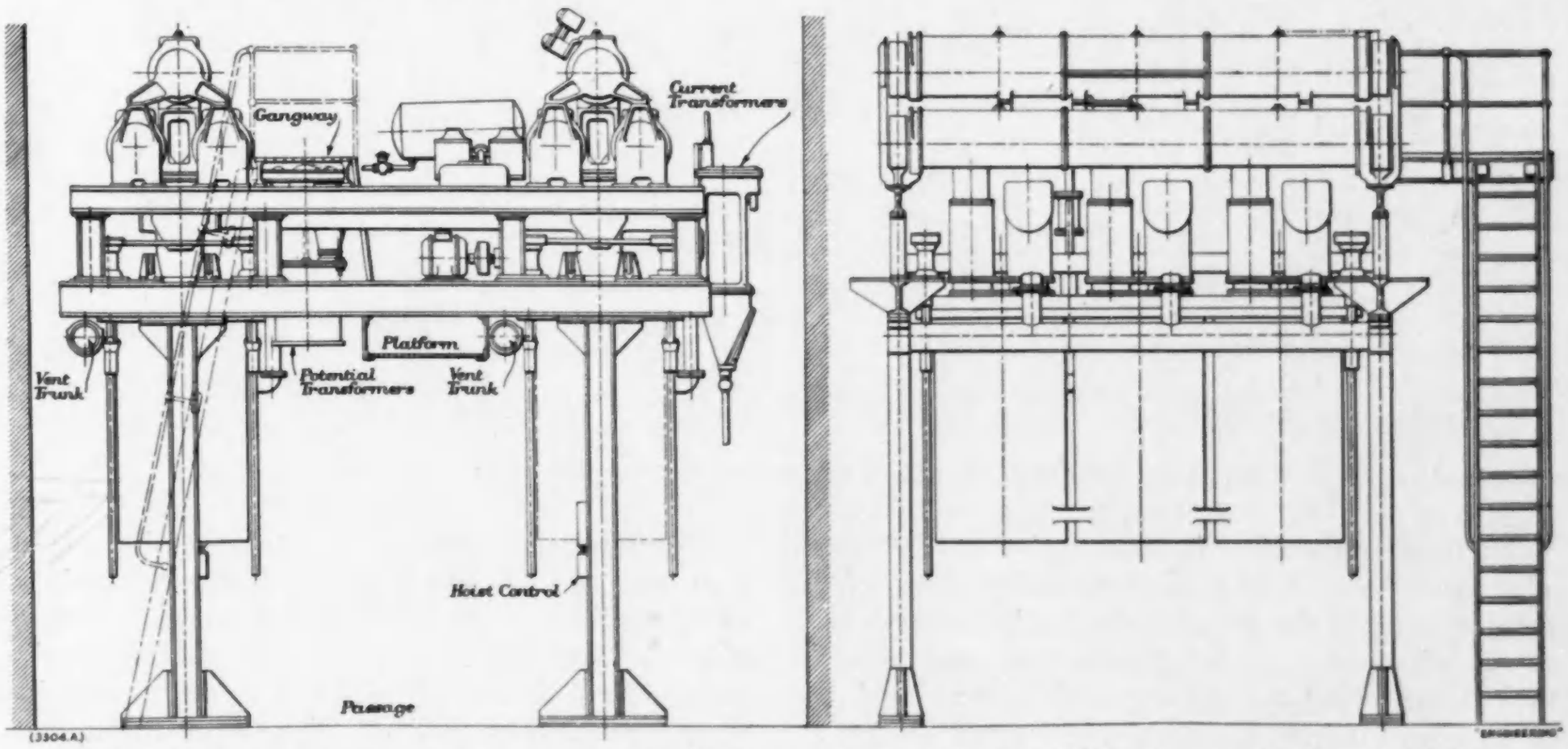
Fig. 1.—Main 11,000 volt, 3 phase, 50 cycle, metalclad switchboard at Blackburn Meadows Generating Station, Sheffield.

cibanite is an insulating material in which the insulating medium is incorporated in the paper slurry before the paper is made, the result being that its insulating and mechanical strengths

Fig. 3.—View of the top of the main switchboard along the gangway, showing the duplicate set of busbars and secondary reservoirs.

mounted on the top-plate of each breaker, with a piston connected to a rack, which is permanently in mesh with a pinion. This pinion is mounted on a shaft which extends across all three phases and carries three bevel wheels, one of which is placed over the centre line of each phase. These wheels are, in turn, connected through bevel gearing to two guide rods, which rotate in brackets suspended from the underside of the top plates, as will be clear from fig. 10. The upper ends of each pair of guide rods are also coupled together by a second pair of bevel wheels and an auxiliary shaft, which lies directly below the top plate. This ensures that the system moves together as a whole. As will be clear from fig. 6, a twelve-start thread, with a lead angle of approximately 45 deg., is cut on the lower end of each guide rod and this engages with the nuts at the ends of the cibanite beams which carry the moving contacts. The rotation of the guide rods, therefore, causes the beam to rise or fall and the breaker to be closed or opened.

These operations are effected from the control room, where the closing of the appropriate control switch energises the coil of an electrically-operated valve, causing the exhaust port on the cylinder to close and the inlet port to open. Compressed air is thus admitted from the secondary storage reservoir described below and the operating shaft revolves through the 1½ turns necessary to close the switch.



Figs. 4 and 5.—End and front elevations of a 3-phase unit of the main 11,000 volt metalclad switchboard.

both through and along the laminæ of the fabric are better than those of bakelite as ordinarily manufactured.

As already stated, the closing of these circuit breakers is effected by compressed air, the mechanism used for this purpose being shown in figs. 11 and 12. As will be seen, it consists essentially of a cylinder, When this has taken place, the control switch is moved to its off position, de-energising the valve coil and allowing the exhaust ports to open.

The circuit breaker is held in its closed position by a latching mechanism, which is attached to the upper end of the rack. As shown in fig. 12, this consists of a pair of links on which a roller is mounted,

the latter being guided throughout its travel by an extension of the pins on which it turns. When the rack reaches its upper position, that is, when the circuit-breaker is closed, this roller passes over the surface of a curved table and is engaged by a spring catch and locked. Its position is, however, unstable, and it will therefore roll over the edge of the table should the catch be released. When the shunt trip coil is energised, either by the control room operator or owing to the occurrence of a fault or short-circuit, the tail of the catch is pulled down by the plunger

become energised, the catch will be lifted, thus enabling the air pressure to open the exhaust valve by compressing the springs supporting it. This enables the breaker to open quickly, when it is closed on a fault, by providing an extra outlet for the compressed air. To prevent the breaker being held closed against a fault, an electric clutch is provided between the handle of the switch in the control room and the shaft on which its operating contacts are mounted. The coil of this clutch is connected in series with the tripping coil of the

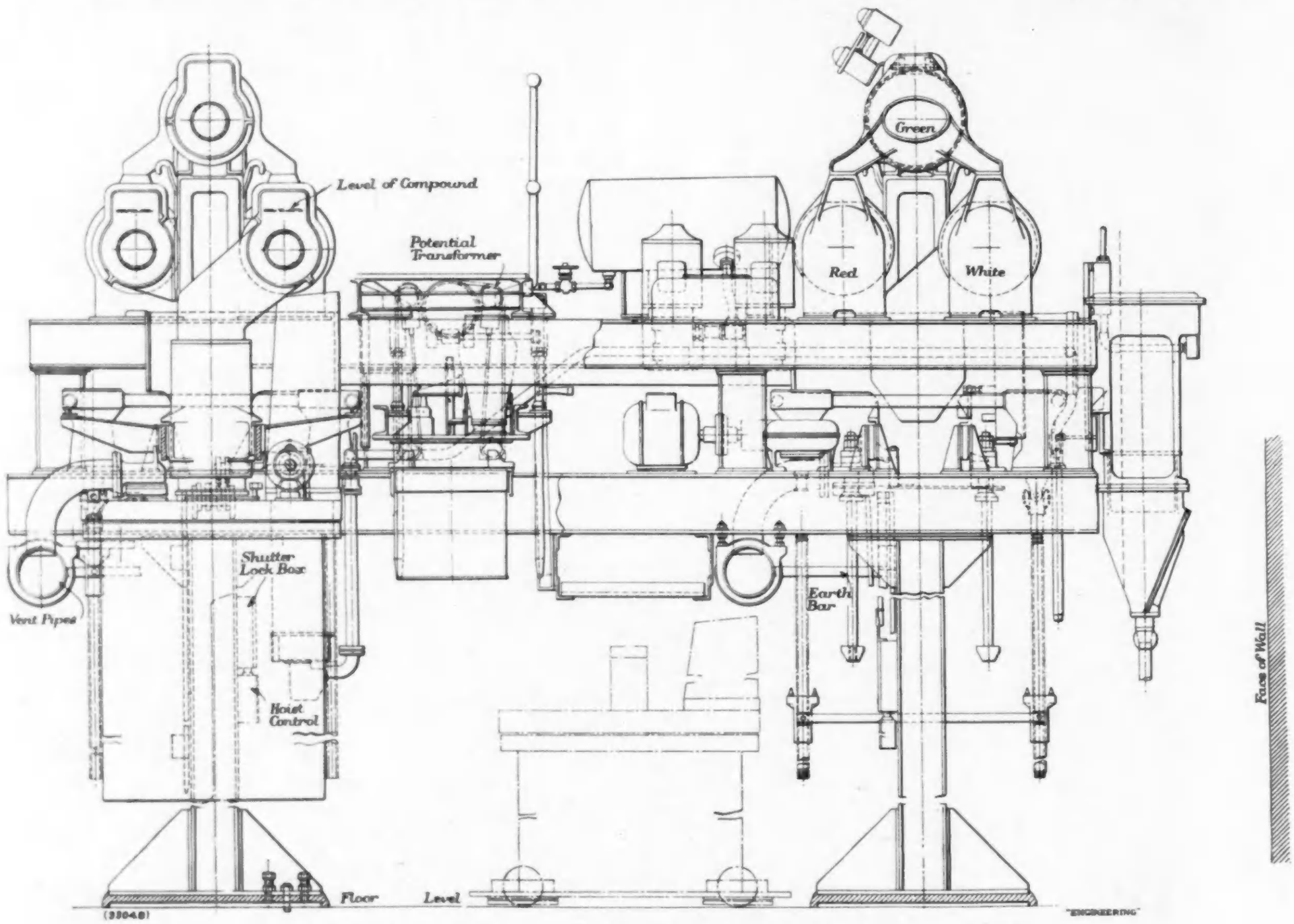


Fig. 6.—Section through one of the units, showing details of construction.

and the roller therefore is freed and rolls over the edge of the table, thus causing the racks to fall. As there is no air in the cylinder, the moving contacts of the circuit breaker are left free to move downward, their travel being assisted by torsional accelerating springs.

It will be noticed from fig. 12 that the operating cylinder is provided with a second exhaust valve. This is normally maintained closed by springs, which are of just sufficient strength to balance the atmospheric pressures, and by a set of toggle links. These links are also prevented from collapsing by a catch, which is coupled through a rod to the trip coil. Should the cylinder be full of compressed air and the trip coil

breaker, and is arranged so that it disconnects the controller contacts from the handle when it is energised. Obviously, if this coil becomes energised as the breaker is being closed, the contact shaft will be automatically released and will be returned to its neutral position by springs. The circuit controlling the valve will therefore be broken, so that the exhaust port on the operating cylinder will open and the breaker will be released, as already explained. Further, as the controller handle must be returned to neutral, in order that the clutch can be reset and a further attempt made to close the breaker, it is impossible for "pumping" to occur.

The principle embodied in the equipment we have

just described is, of course, not new, since tests were made with switchgear operated by compressed air as long as thirty years ago and it has also been used to some extent on traction equipment. Its use here is nevertheless of considerable interest, since it is an attempt to find an alternative to the solenoid and the motor, which have so far been exclusively employed for closing switches whose moving parts were too massive to allow them to be operated manually at a speed sufficiently high to prevent arcing at the contacts and the damage and disturbance to which

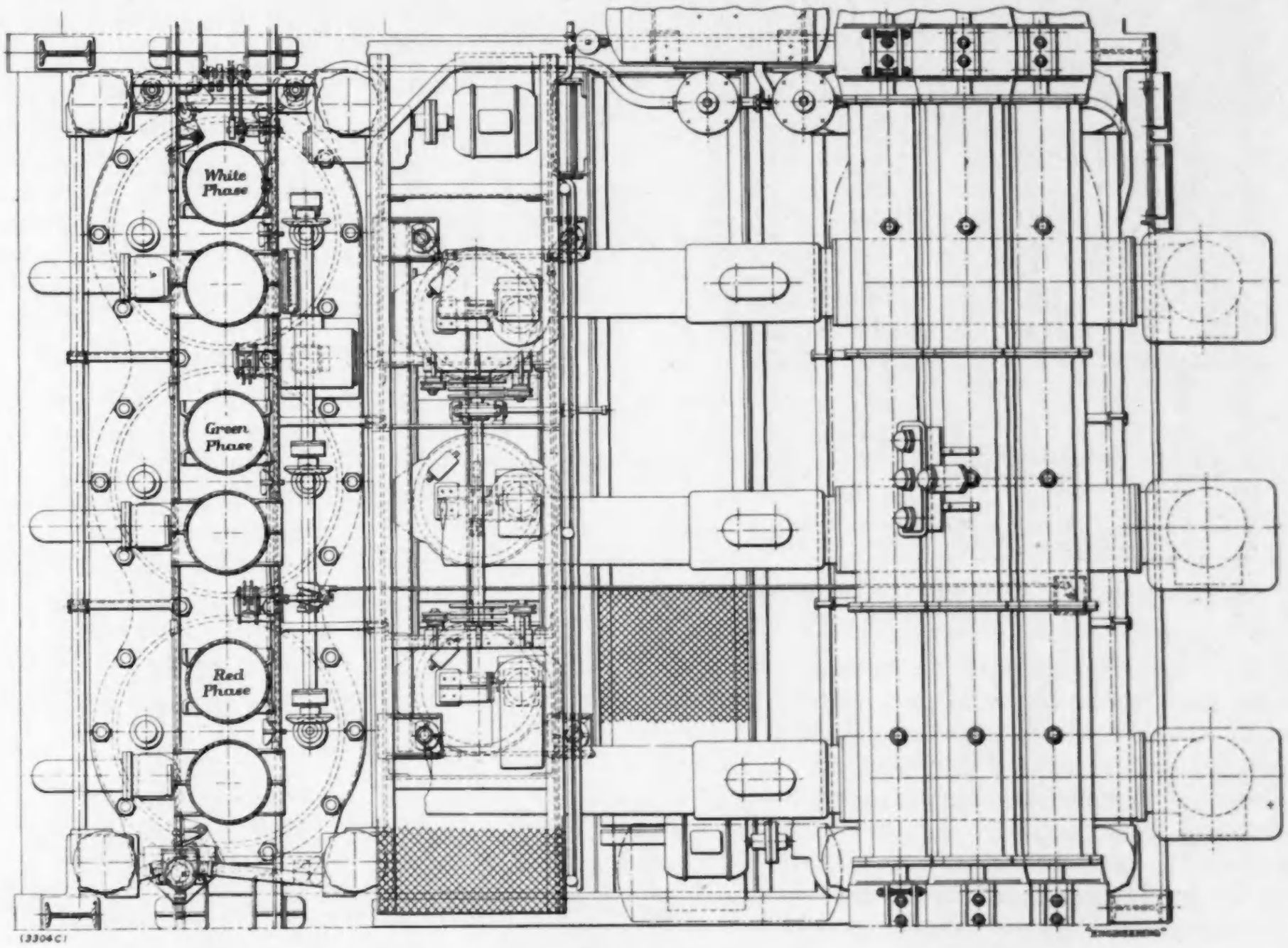
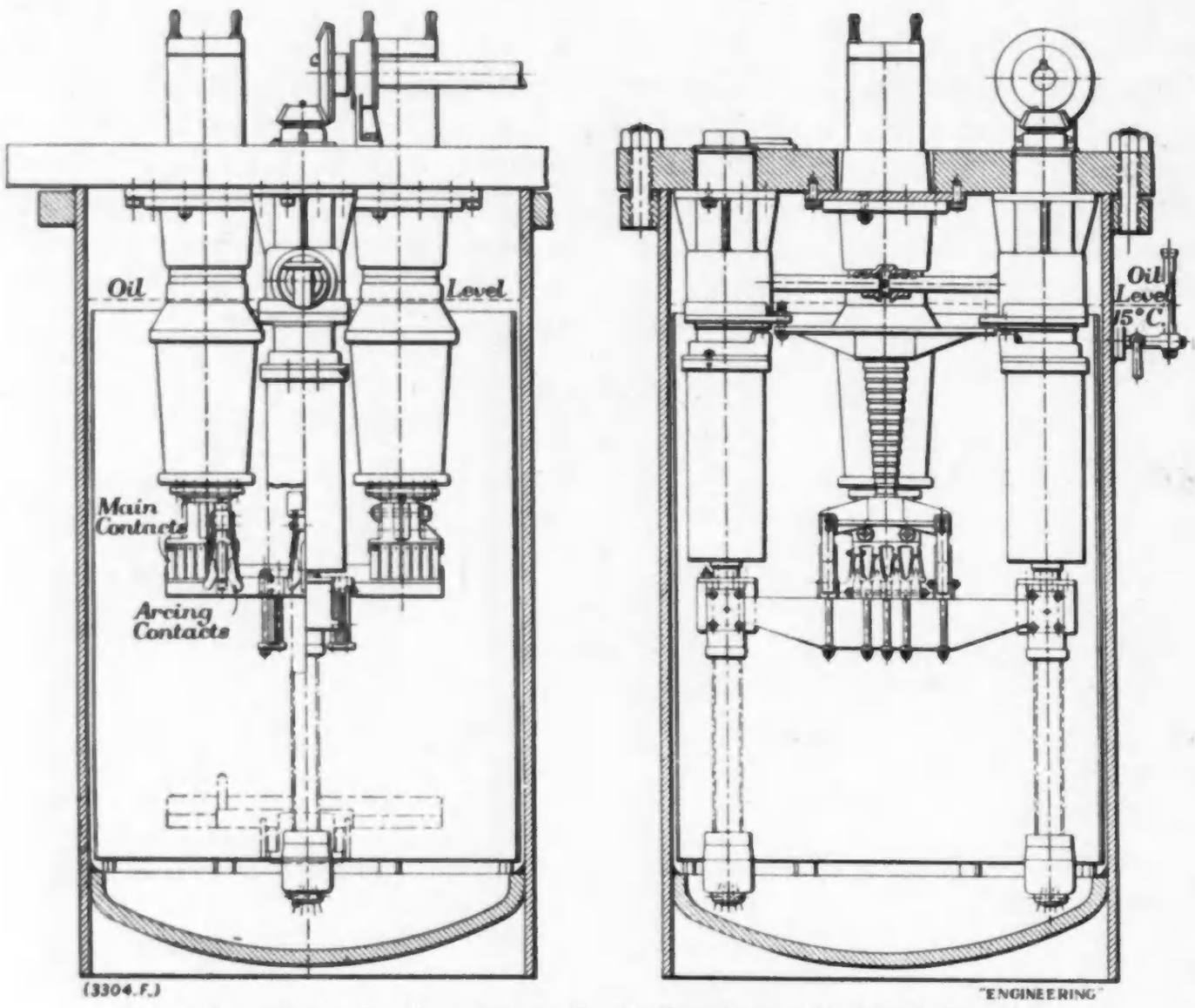


Fig. 7.—Plan view of one of the units, showing arrangement of equipment.

this gives rise. That some such alternative is desirable will be clear when it is recalled that a solenoid, though cheap to install and simple to operate, necessitates the presence of a direct-current supply of a capacity commensurate with that of the circuit-breaker. Again, in such a circuit-breaker the contacts have to be moved both rapidly and through a considerable distance, this necessitating the use of a coil with a large number of ampere-turns. If these are obtained by using a small current and a large number of turns the breaker cannot be closed quickly, while if a small number of turns are employed the resulting current will necessitate the installation of a high capacity battery. On the other hand, operation by means of a motor, though it eliminates the use of a battery, is more expensive initially than the use of a solenoid and, since it involves the winding-up of a weight or the compression of springs, is also much slower in action. Inherently, therefore, compressed air, which is instantaneous in operation and can be easily generated and cheaply stored, offers distinct advantages. Its re-introduction for this purpose will therefore be watched with interest, especially as since the early days many improvements in the necessary pipe lines, fittings, and other equipment have been made. The compressed-air installation is considered cheaper in first cost than the equivalent batteries, as it does not need to be installed in acid-proof rooms, while it should require less attention and is certainly simpler.

The compressed air necessary for operating the circuit-breakers in the way we have described is obtained from two electrically driven compressors which are mounted over the bus-section switch. One of these compressors is driven by a 2.5 h.p. three-phase motor fed from the auxiliary supply of the station, and the other by a direct-current motor of the same output, which is connected to a battery and acts as a stand-by. These compressors deliver air at a pressure of from 100 lb. to 115 lb. per square

inch through a water-trap and cooler to a main storage reservoir, which has a volume of 35 cub. ft. This reservoir is fitted with automatic governors, which controls the starting up and shutting down of the com-



Figs. 8 and 9.—Sections through single phase oil circuit breaker, 1,500,000 kVA breaking capacity.

pressors. By adjustment of the appropriate cocks the compressors can be arranged to supply the bus pipe direct. Moreover, the compressors, governors, water trap, and air cooler can be disconnected without affecting the supply to the bus pipe from the main reservoir. The main reservoir is connected through a reducing valve to the bus pipe, which is connected to secondary reservoirs on each switch unit; these are visible in fig. 3. The introduction of the reducing valve ensures that the breaker shall be operated at a constant speed. The valve is adjusted to maintain the air in the bus pipe at a pressure of 97 lbs. per sq. in. The volume of the secondary reservoirs is 3.7 cub. ft., which is sufficient to close a breaker at normal speed. From this point the air passes through valves to a point on each side of the switch where the pipes are automatically coupled to the operating cylinder. The operating circuits of these valves are automatically selected when the circuit-breaker is raised or lowered, thus enabling the air supply to be diverted when a breaker is transferred from one set of bars to the other. The air system as a whole is of sufficient capacity to allow a breaker to be closed a large number of times in rapid succession without any decrease in speed, as the secondary reservoirs regain their operating pressure in about 30 seconds, and the main reservoir is automatically supplied with air from the compressors when the pressure in it falls below a predetermined value. After passing through the operating cylinders the air escapes into the open through exhaust valves. It may be added that all the air circuits were tested hydraulically at a pressure of 300 lb. per square inch and pneumatically at a pressure of 150 lb. per square inch before installation. The compressors, reservoirs, and other pneumatic equipment were manufactured by The Electro-Mechanical Brake Company, Limited.

Returning to the circuit-breaker proper, that part of the equipment for each phase which, as already described, is suspended from the top plate, is contained in a separate cylindrical tank for each phase, as clearly illustrated in fig. 13, which shows the tanks lowered for an inspection

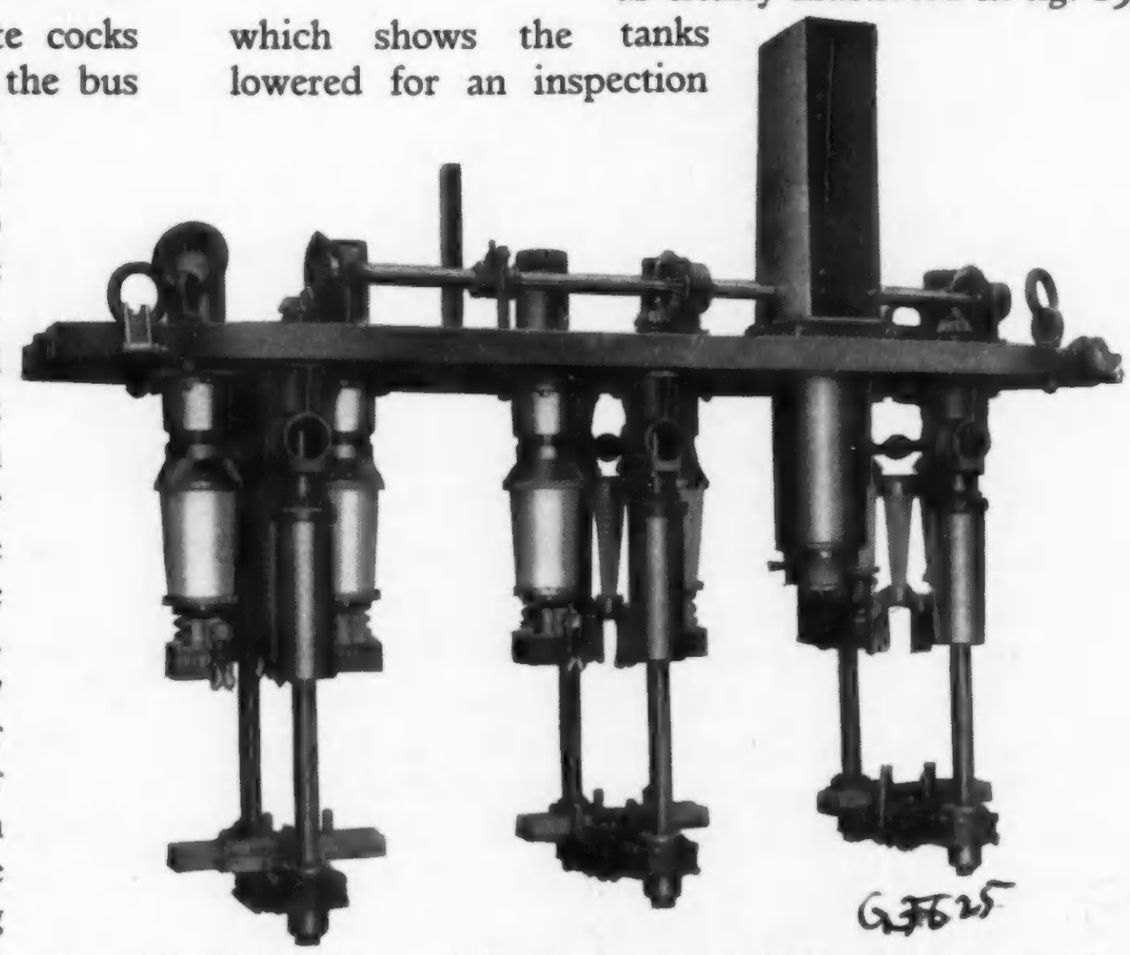


Fig. 10.—View of one of the 3-phase circuit breakers removed from its tank.

of the contacts. Each tank has a lap-welded body $\frac{3}{4}$ in. thick and a bottom, which consists of a domed steel pressing. This pressing is $1\frac{1}{4}$ in. thick and is shrunk into and then electrically welded to the body.

After manufacture, each tank, together with its top plate, was subjected to a hydraulic pressure of 800 lb. per square inch and was required to withstand that pressure without distortion. The three tanks forming a unit are coupled together at the top by a steel flange plate into which they are welded, and lower down are also joined by steel bars, which are welded to the bodies in line with the bottom. Connection to the top plate is made by high-tensile steel bolts, the joint being metal-to-metal and no gasket being used. Each tank is lined with elephantide, which is placed away from the metal, so that there is always a layer of quiescent oil between it and the tank.

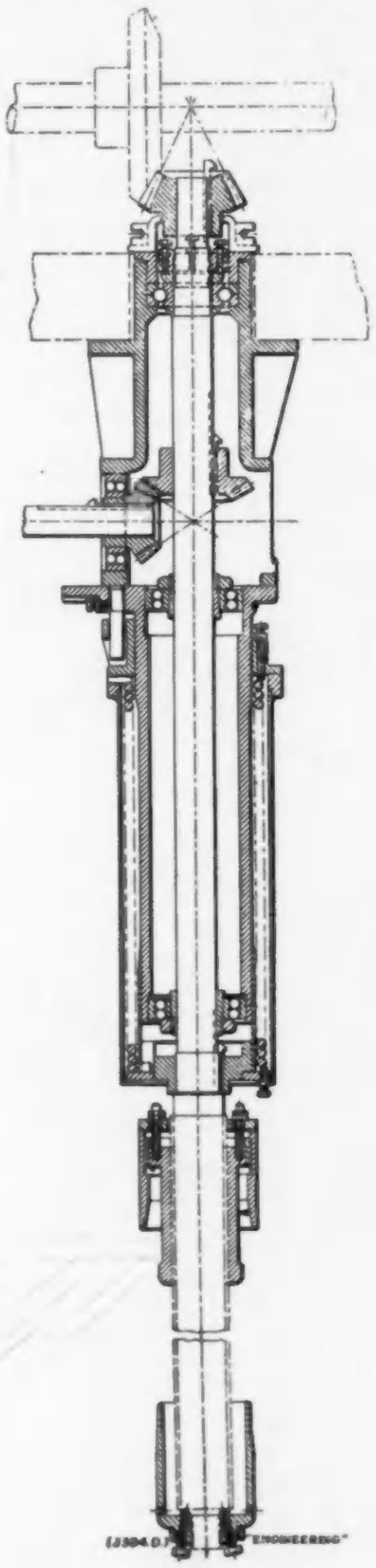


Fig. 11.—Closing mechanism of oil circuit breaker.

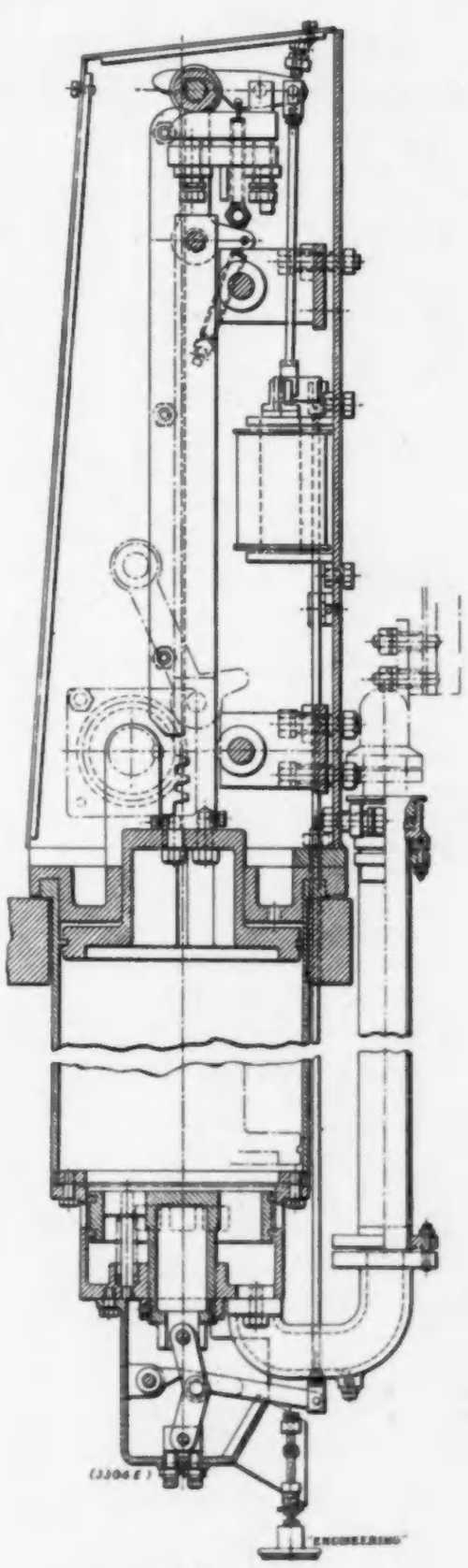


Fig. 12.—Closing and latch mechanism of oil circuit breaker.

Each unit can be lowered to, or raised from, the floor by a hoist which is operated by a 5 h.p., three-phase motor running at 1,425 r.p.m. This motor is controlled by a switch mounted on the face of the pedestals, and drives a worm through double helical gearing. The worm wheel with which this worm engages is mounted on a shaft forming the top of one of

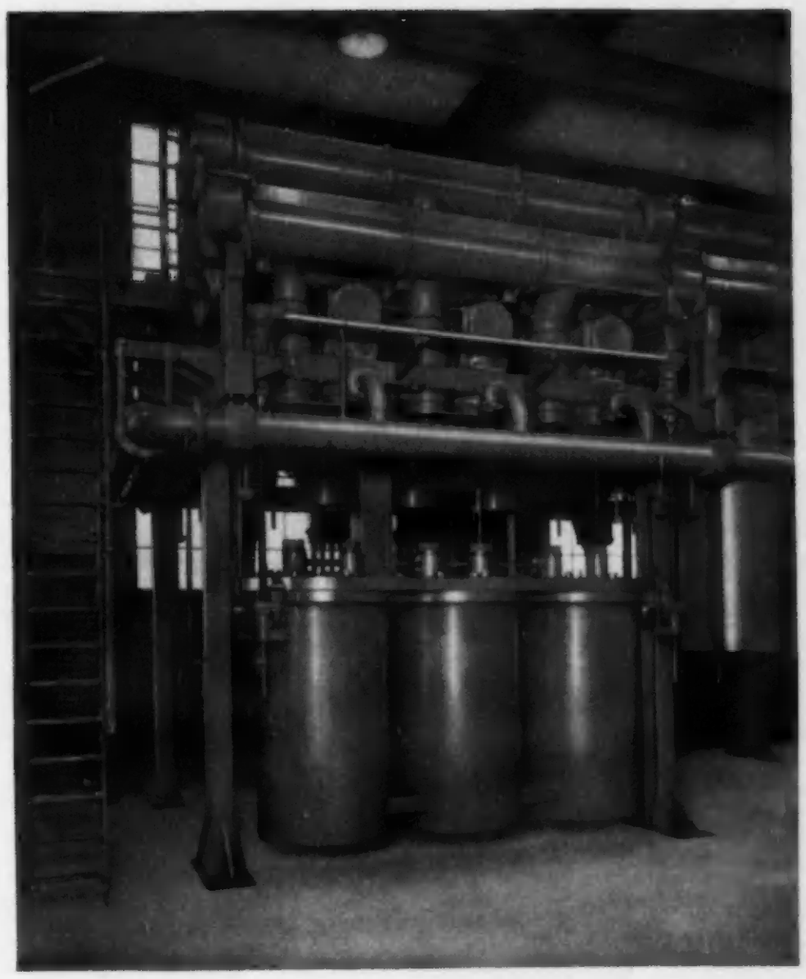


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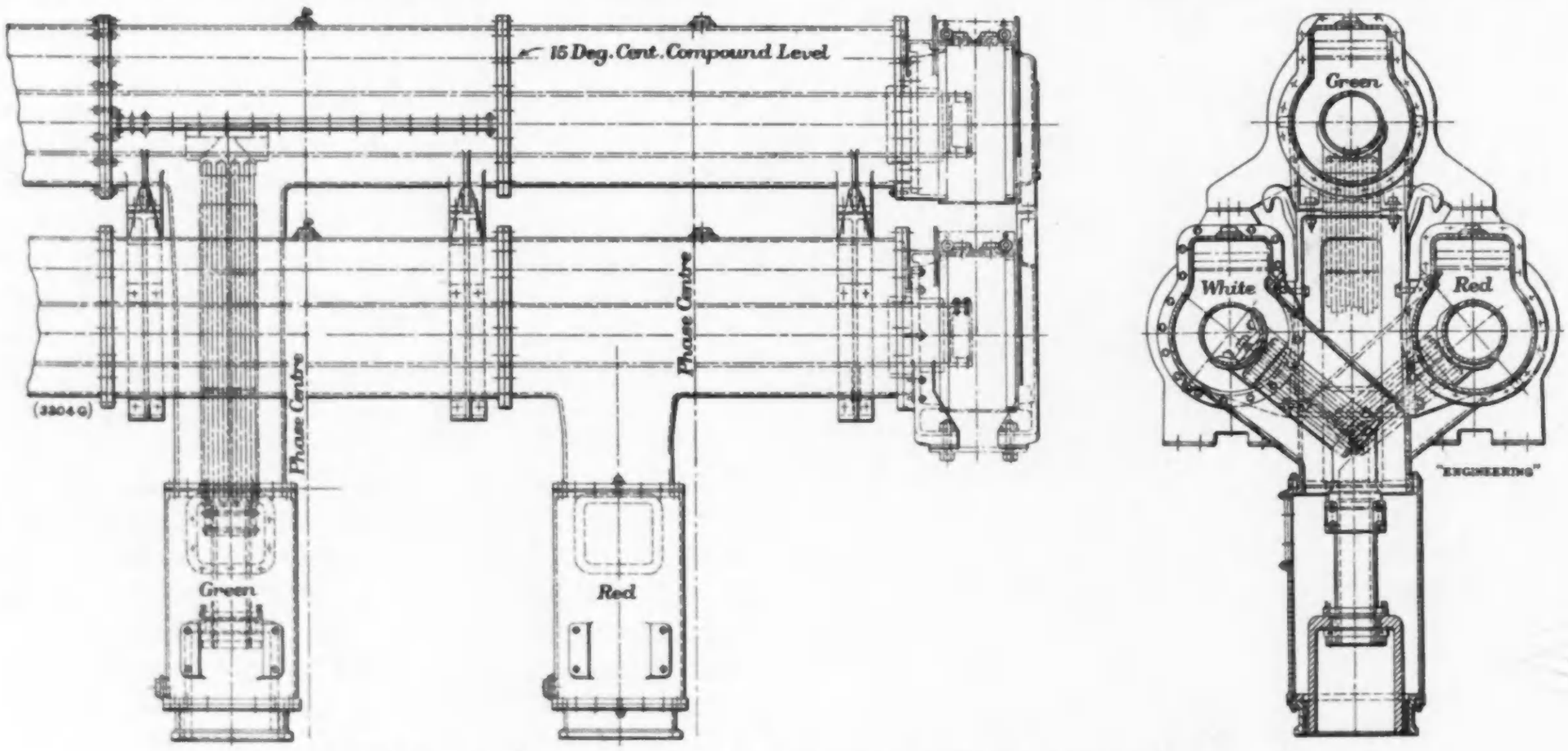
Fig. 13.—One of the ten units forming the main switchboard : view with the breaker lowered.

four vertical lifting screws. The four screws are connected by a heavy-duty roller chain. These screws are mounted on thrust bearings and are universally jointed ; they carry a nut block which engages with lugs on the tank structure. The screws are able to swing freely from the universal couplings when they are disengaged from the tank. To lower the tank the motor is started up and the screws revolve, so that the nut blocks descend, carrying the tank with them. Lowering is continued until the tank is in the position shown in figs. 13 and 14 and its weight has been taken by a truck, which is run under the structure. A further revolution of the screw then allows the nut blocks to be disengaged from the lugs, so that the tank can be moved away for inspection or repair. To replace the tank in its working position, it is first run under the structure and the nut blocks are once more engaged with the lugs. The motor is then started up, and as the screws are free to swing immediately the tank is raised off the truck, the former automatically moves into its correct position. This arrangement enables rails or other similar expedients for ensuring accurate alignment of the transfer truck with the structure to be dispensed with, since so long as the tank is placed under the structure in a position where the nut blocks and lugs can be engaged it can be raised. Flexibility is therefore greatly increased. Particular attention may

be drawn to the fact that the breaker is maintained in the operating position by the screws alone and that, as the nut blocks engage with the lugs on the tank, the switch cannot make contact with the busbars with its contacts exposed. To prevent the tank being removed, leaving the breaker plugged in to the bars, the lowering operation is effected in two stages. When the hoist motor is first started, the breaker is disconnected from the bars and lowered a short distance to the isolating position, where the live contacts are covered by shutters. Further downward movement of the top plate is, however, prevented by stops, though the tank can be lowered and the contacts exposed after the securing units have been removed. If, however, it is desired to lower the complete switch unit, these stops can be rotated out of engagement by a hand lever. In either case the tank is prevented from turning by guides while it is being lowered. An indicator is provided to show when the circuit-breaker has been raised to the correct service position. The truck on to which the tank is lowered consists of a platform of $\frac{3}{4}$-in. steel plate, each corner of which is supported on an axle-box. Each axle-box carries a short spindle, on both ends of which a roller is mounted, and is rotatable so that it can be turned round into four different positions by a bar and there locked by a catch. When the tank has been lowered on to the truck, the latter can be run out free of the structure and, after suitable adjustment of the rollers, subsequently moved off in any desired direction.

Fig. 14.—The complete main switchboard erected at Witton Engineering Works, before despatch to site.

The circuit-breakers are connected to the busbars through isolating contacts which, as shown in figs. 15 and 16, consist of a varying number of plugs of special high conductivity springy copper alloy, with spherical ends, the normal current rating of which is 200 amperes. This design of plug has been found to give line contact, even when the engagement is not truly vertical. These plugs are mounted on the top of the circuit-breaker terminals and engage with copper sockets which are protected by porcelain sheaths. The lower ends of these sheaths are cemented into non-magnetic casings, which are bolted direct to the respective housings. All the isolating contacts are protected by dust-tight shutters which open and close automatically as the circuit breakers are raised and



Figs. 15 and 16.—Front and end elevations of busbar chambers.

lowered. When the circuit breaker has been removed, these shutters are locked by Yale type locks, which are operated from a central position.

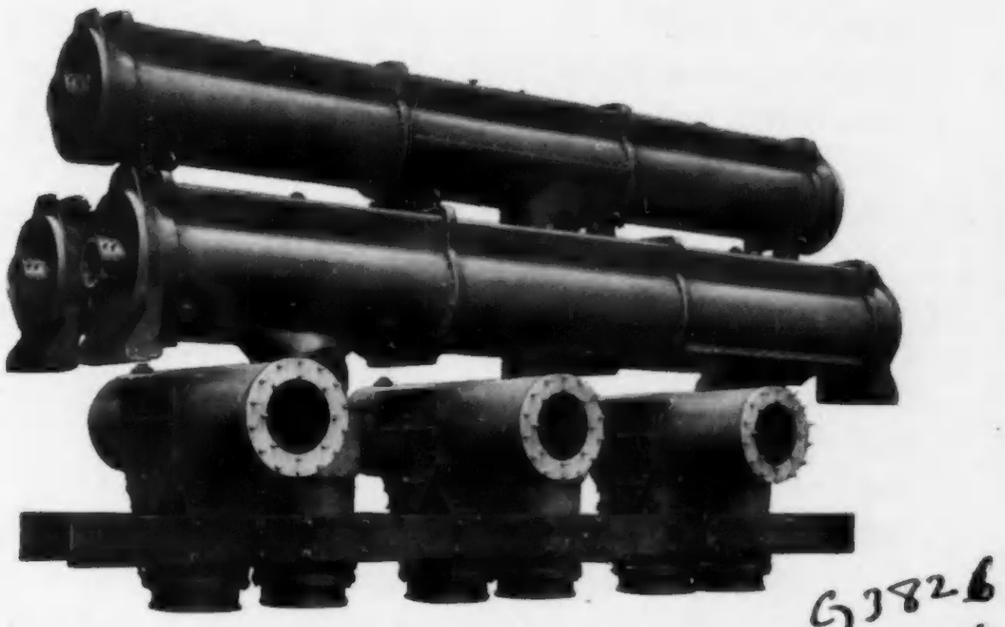


Fig. 17.—Tubular busbars fitted into compound-filled busbar chambers.

The sockets are connected to the busbars which as shown in fig. 17, consist of hard-drawn high-conductivity copper tube of sufficiently large section to prevent any undue temperature rise, due to the combination of the self induction, or skin effect of the bar; its proximity to adjacent bars, and to the blanketing effect of the compound. They are placed in trefoil formation, as shown in fig. 14 (which is a view of the equipment in the works) an arrangement which, together with the tubular section, is so effective that the ratio of alternating-current to direct-current losses is approximately unity; they are supported on bakelised Manilla paper plates. These plates are fixed into the end of each section of the busbar chamber, and the insulation is increased at these points by the use of bushings of similar material. Sufficient strength is thus provided to withstand the maximum electro-mechanical force, which may be exerted in the busbars. The ends of each section of busbars are coupled to the next by drawn bars of the same curvature as that of the bars, on the face of which serrations or reeds have been cut. The busbars are anchored at the bus section circuit-breaker so that they are free to expand in both directions, the sockets being connected to the busbars by a number of stranded copper cables to ensure that there is no strain on the porcelain insulators due to expansion. The cables are arranged in circular formation to reduce the losses caused by skin effect.

A separate busbar chamber is provided for each phase. These are constructed of high tensile non-magnetic alloy and are mounted on the pedestals as shown in fig. 17, so that a space is left between adjacent units. This enables the busbars to be coupled up after erection has been completed. The space is then enclosed by a metal band which is passed round the ends of the

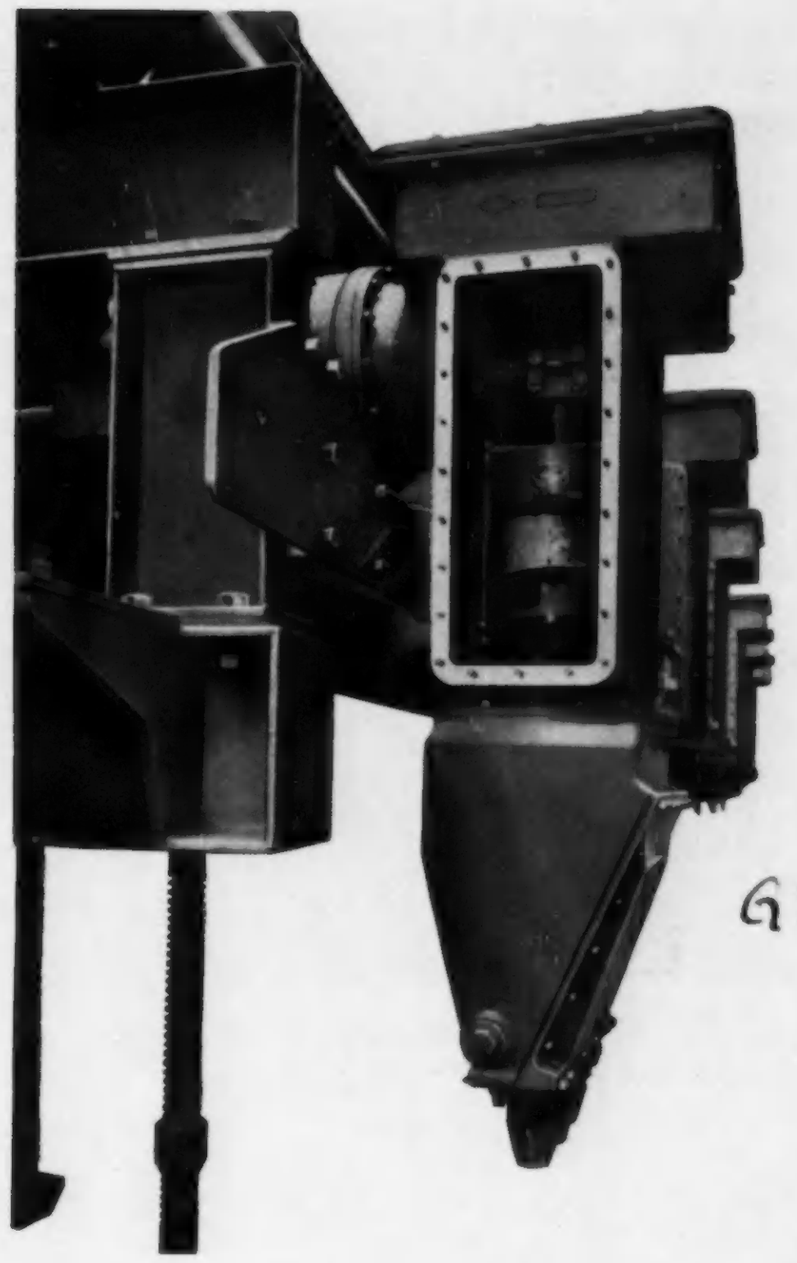


Fig. 18.—Current transformer chambers are mounted at the rear of each unit.

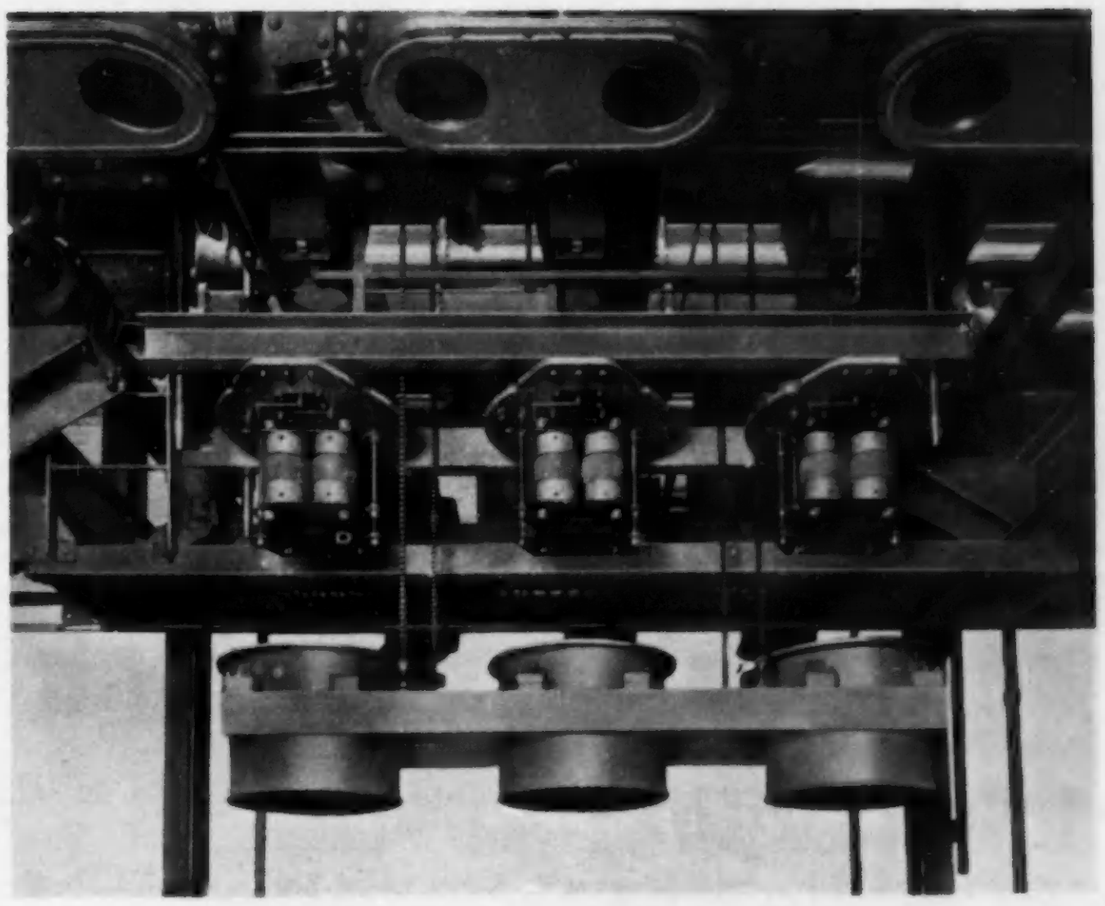


Fig. 19.—View underneath one of the units, showing vertical isolation arrangement of potential transformers.

chambers and clamped in position. Compound is finally poured in through a filling orifice at the top, and in this connection it is worth noting that a continuous ventilated air space is left above the compound along the whole length of the bars, so that a free flow and expansion of this material are ensured and trapping cannot occur. In order to prevent heating, due to the circulating current in the busbar chambers, the casing of each phase is insulated from those of the other phases and from the supporting frame work by a layer of bakelised Manilla paper $\frac{1}{16}$ in. thick. The busbar chambers are electrically continuous throughout their length, and each phase is earthed at one point only, through current transformers in the secondary of which is a relay connected in a bell circuit. An alarm is therefore given immediately if a circulating current should be caused by the accidental earthing of a casing.

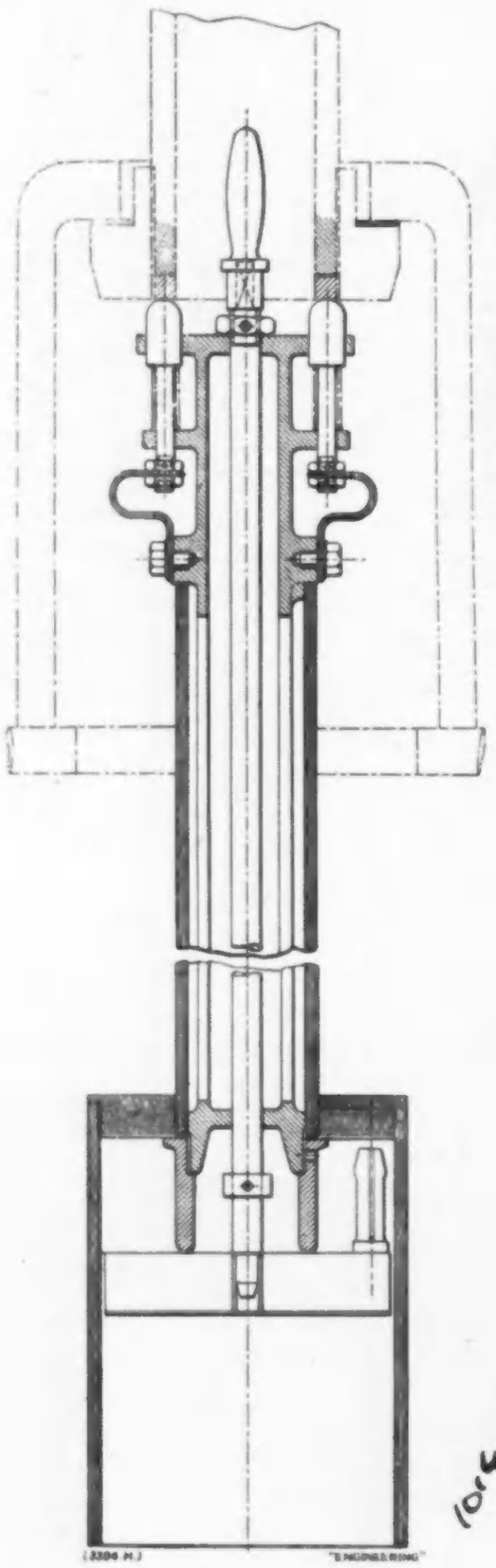
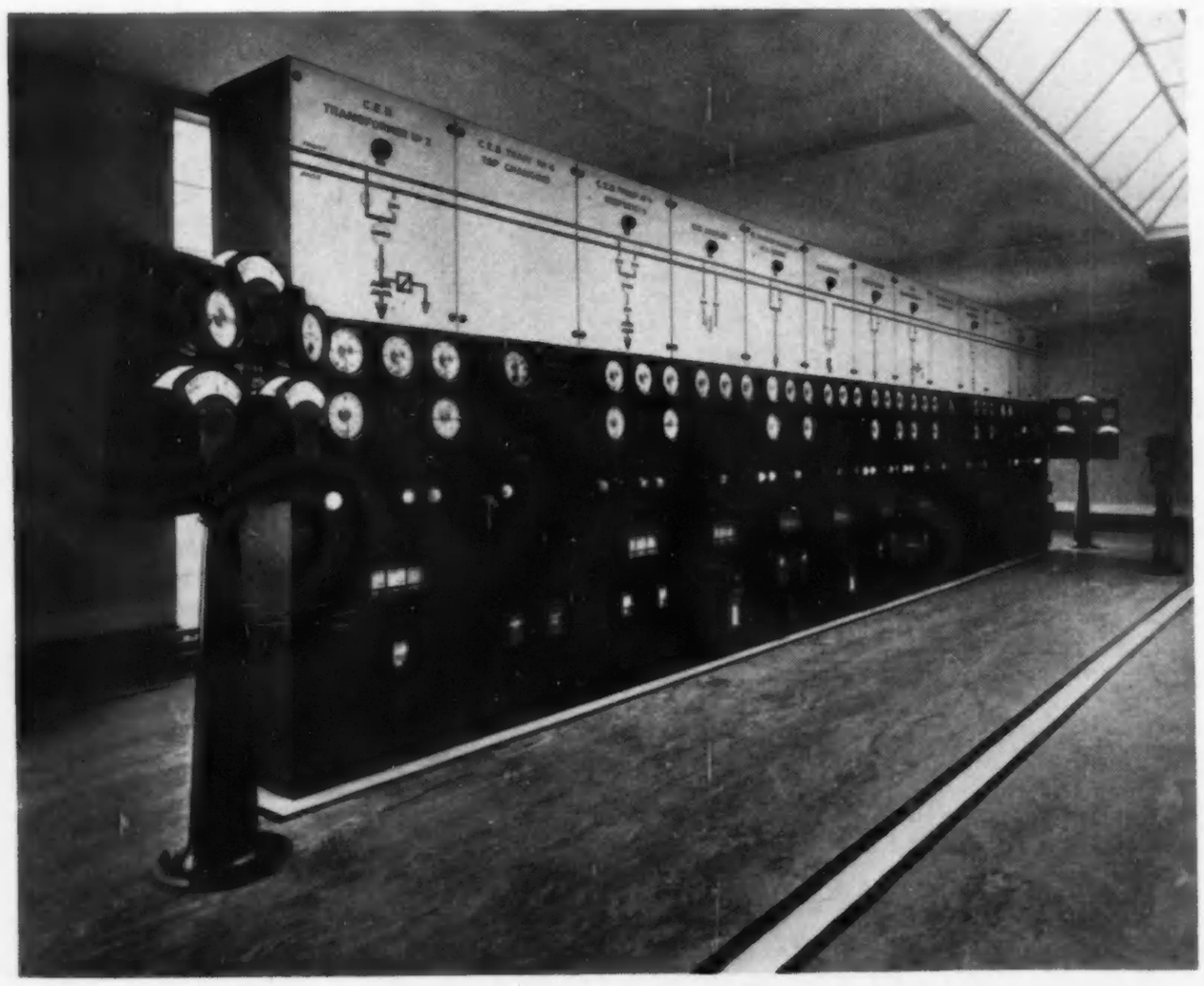


Fig. 20 (left).—Feeder earthing equipment.

Fig. 21 (below).—The main control switchboard installed in a separate room. Note the automatically operated mimic diagram at the top of each panel.



The current transformer chambers, one of which is illustrated in fig. 18, are mounted at the rear of the circuit breaker and are connected to the isolating contacts by trunking to which in turn the cable boxes are fitted. They are made of the same non-magnetic material as the busbar chambers and are filled with semi-fluid compound. The position of the potential transformers of which there are three to each unit, will be clear from fig. 4. This equipment is, as shown in fig. 19, arranged for vertical isolation and can be raised or lowered manually by gear which is operated from the lower platform of the structure. In the isolated position they rest on stops, while further operation of the lowering gear drops the tank so that the transformers themselves can be inspected. The isolators are designed so that they break circuit under oil.

A final interesting point about this equipment is that any feeder can be earthed through its associated breaker. To do this the breaker is first lowered into its bottom position. The earthing equipment, which, as shown in fig. 20, consists of a set of three extension contacts for the feeder terminals and a second set for the busbar terminals, is then fitted on. The latter contacts are connected together and are coupled to the earth bar on the unit by a flexible cable. Extension pillars, which prevent the circuit breaker from being raised to its normal operating position, are then fitted and the operating circuits are connected up by jumper plugs. Next, the feeder shutters are opened by the use of a detachable handle at the shutter lock box, and the circuit breaker is then raised until it is stopped by the extension pillars, in which position the earthing extension contacts are in contact with the socket

blocks in the feeder spouts. The busbar shutters are then locked closed, causing an auxiliary switch in the hoist gear circuit to open so that the circuit breaker cannot be lowered. Finally, the circuit-breaker can be closed so that the earthing of the feeder is completed.

CONTROL BOARD FOR MAIN SWITCHBOARD.

The 1,500,000 kVA 11,000 volt metalclad switchgear is controlled from a switchboard, fig. 21, situated in the control room. The board consists of a series of instrument panels with a mimic diagram of the system mounted above each panel.

The panels are of black enamelled polished steel with bevel edges. The instrument section of each panel consists of a single sheet on which is mounted the control handle for the corresponding oil circuit breaker of the metalclad switch unit, together with measuring instruments, regulating apparatus, protective devices and indicating lamps.

The mimic diagram above each panel shows the attendant the electrical circuit which is controlled from that panel, while an indicating lamp above the diagram lights when the circuit has been tripped by a fault. The diagram is rendered in black lines on a white background.

10145-7

Fig. 23.—Works 440-volt metalclad switchboard, with manually operated oil circuit breakers. The current capacity of the centre units is 4,000 amperes.

Immediately adjacent to the board are pillars upon which are mounted duplicate synchronising instruments. The auxiliary apparatus and connections behind the panels are completely enclosed in steel cubicles having doors at the back.

11,000 VOLT AUXILIARY SWITCHBOARD.

The power supply for works auxiliaries is taken from the low tension side of three 1,500 kVA transformers. The high tension supply for these transformers is controlled by a G.E.C. 500,000 kVA, 11,000 volt metalclad switchboard of the duplicate busbar pattern, fig. 22, consisting of five units, which control respectively two incoming and three outgoing feeders. This switchboard is of the same general type as the main switchboard but differs in detail. The main points of difference are, firstly, that the oil circuit breakers are manually operated instead of by means of compressed air, and secondly, that instead of transferring the circuit breakers so that they are in a position to feed either of two sets of busbars as required, transference from one set of busbars to the other is effected by means of a special revolving turret terminal patented by the G.E.C. Indicators on the front tell at a glance to which set of busbars the breaker is connected, and whether the latter is "in" or "out."

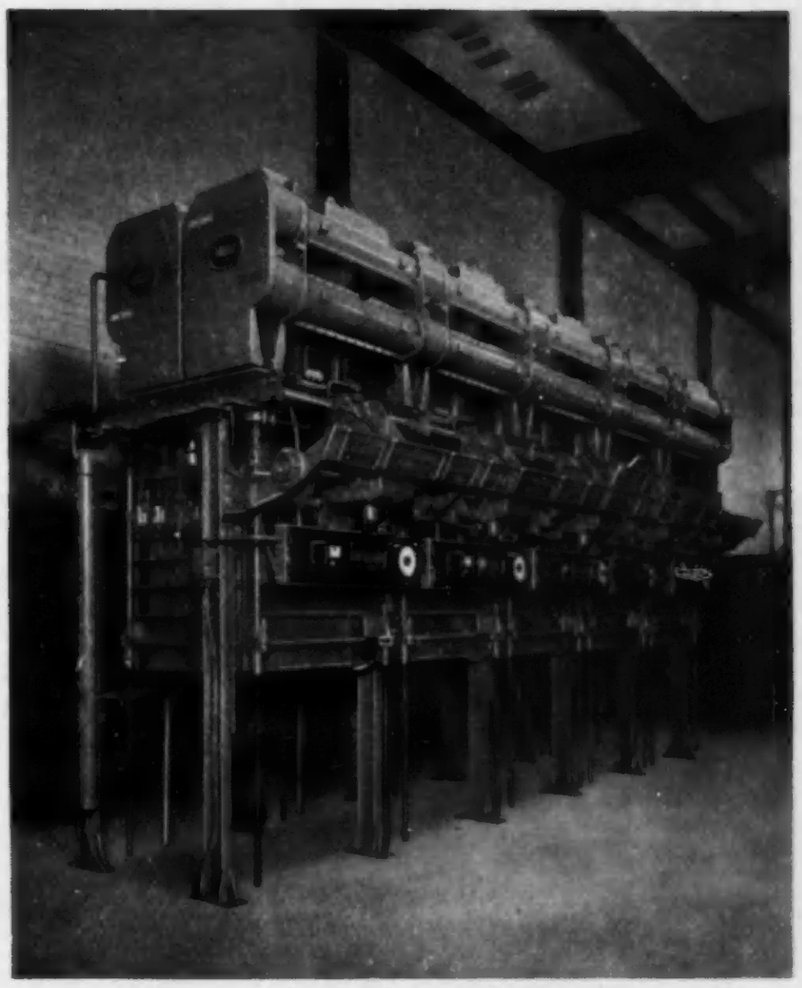


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Fig. 22.—11,000 volt auxiliary metalclad switchboard provided with electrically operated oil circuit breakers of 500,000 kVA breaking capacity.

The mechanism by means of which the circuit breakers are operated, embodies the "loose handle" feature which renders it impossible to hold the

breaker closed on a fault. The drive from this to the breaker linkwork is by connecting rods which automatically disengage as the breaker is lowered.

WORKS L.T. SWITCHBOARD.

For controlling the low tension supply to the works auxiliaries, a further G.E.C. metalclad switchboard has been installed, fig. 23, with a busbar capacity of 4,000 amperes at 440 volts. This switchboard controls the three incoming feeders from the low tension side of the transformers mentioned above, also seven outgoing feeders, comprising three boiler auxiliary feeders, two turbine circuit feeders, one for lighting and heating supply, and one to a sub-distribution board. There is in addition a bus-sectionalising unit.

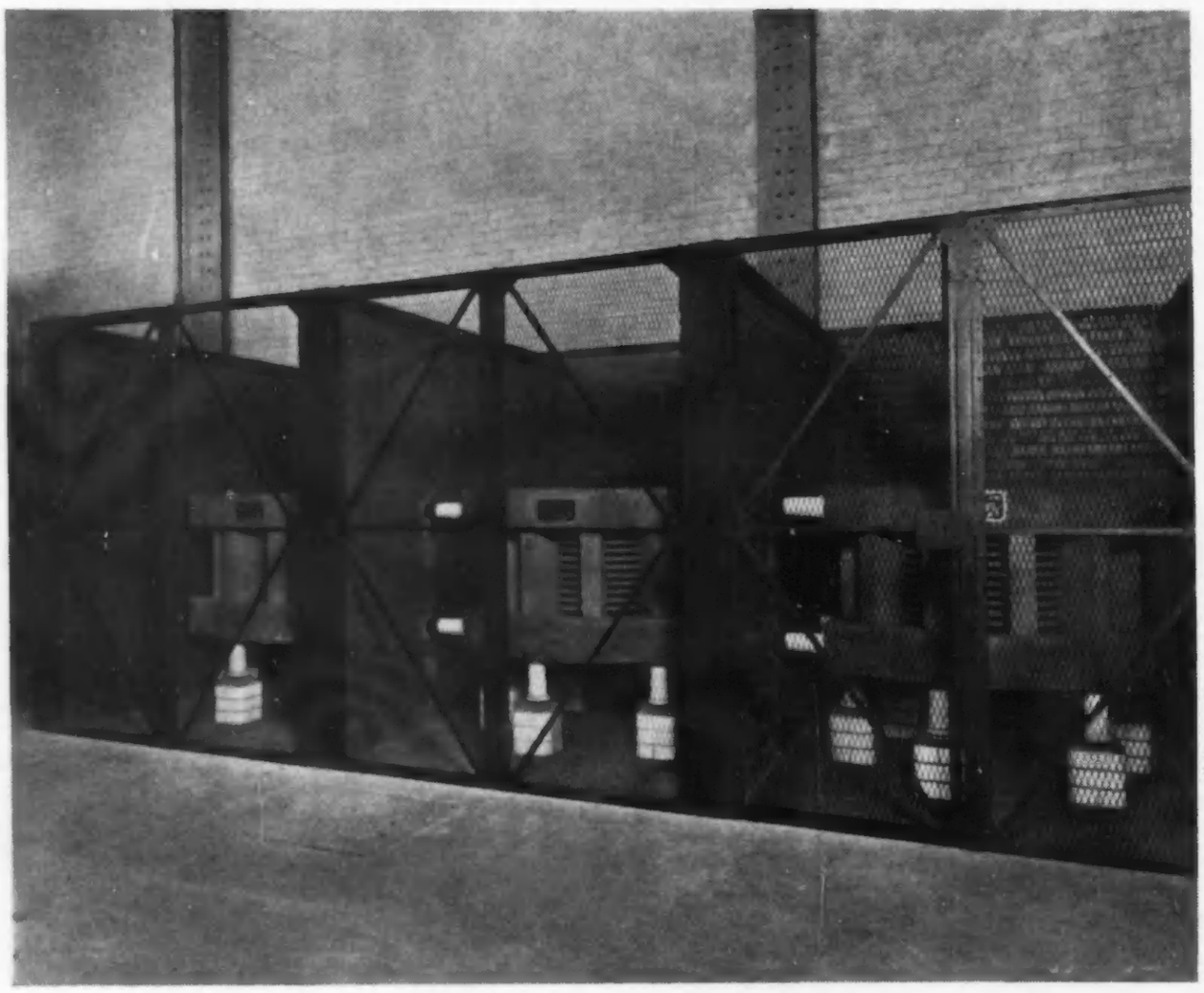


Fig. 24.—One of the two 3-phase banks of 11,000 volt, 50 cycle, 1,140 ampere reactors.

BATTERY CHARGING EQUIPMENT.

The battery charging equipment and distribution panels for two 110 volt 250 ampere hour batteries (manufactured by The D.P. Battery Co., Ltd.), are mounted on a switchboard comprising four slate panels. Charging for both batteries is provided by alternative methods, (1) from a motor generator set, and (2) from a rectifier. Control of the incoming supply is effected on the first panel, the charging apparatus being connected respectively to the opposite ends of a double pole change-over switch. Regulation of battery charging is effected upon the second panel. Upon each of the two remaining panels are mounted four double-pole circuit breakers which switch the battery on to the feeder circuits supplying (*a*) solenoids controlling compressed air for operating the main E.H.T. switchgear, (*b*) tripping circuits throughout the station, and (*c*) indicators and lamps on the main control board and metalclad switchgear.

It should be noted that provision is made so that the battery cannot be charged while it is discharging.

REACTORS.

Two three-phase banks of concrete type reactors have been manufactured and supplied by the G.E.C. for installation in outgoing feeders. These reactor banks protect existing switchgear at Blackburn Meadows (No. 1) Power Station. Each bank has a reactance of 8 per cent on an 11,000 volt, 3 phase, 50 cycle supply with a normal current of 1,140 amperes.

A further reactor bank, installed in an 11,000 volt feeder supplying the auxiliary high tension metalclad board, has a reactance of 5 per cent with normal current of 253 amperes.

The larger reactor units (fig. 24) are of simple but extremely robust construction, consisting of a series of horizontally wound spirals, the winding comprising four conductors connected in parallel which are supported in the recesses of concrete arms. These arms are fitted radially and built up as vertical walls. Layers of concrete arms are assembled on to a heavy concrete base, and a header, or top plate, of similar size is placed on top. The structure thus built up is securely clamped as a solid concrete unit by means of brass rods equally spaced near the periphery of the base and header. The smaller reactor unit is similar to those described except that in this case a single conductor winding is used.

* * * *

The switchgear described in this article was designed, manufactured and supplied by the G.E.C. to the specification of Ernest Morgan, Esq., M.I.E.E., A.M.Inst.C.E., A.M.I.Mech.E., General Manager of the Electricity Supply Department of the City of Sheffield. The panels controlling the gear of the Central Electricity Board were designed to the specification of the Consulting Engineers, Messrs. Merz and Maclellan.

X-Rays: Their Application to Medicine and Industry.—Part I.

By C. G. OSMENT, B.Sc., A.M.I.E.E.

Design Dept., Watson & Sons (Electro-Medical) Ltd.

The author has divided this article into two parts; medical X-ray apparatus and industrial X-ray apparatus. The first part, which is published here, gives an introductory explanation of the nature and theory of X-rays, and subsequently deals with radiological apparatus for medical purposes, and goes on to describe radiographic and therapeutic equipment.

The second part will deal with the industrial uses of X-rays for radiometallography and crystallography.

INTRODUCTION.

SINCE the discovery of X-rays by Rontgen in 1895, the science of radiology has made such great strides that the earlier forms of X-ray tube and apparatus are of historic interest only, and a detailed description of them does not come within the scope of this article. The original type of X-ray tube known as the "gas tube" was used for many years, the generator for supplying the requisite current at high voltage being one or other of the many forms of induction coil. These equipments were erratic in behaviour, difficult to operate and are now obsolete.

The first great advance was made in 1913, when Dr. W. D. Coolidge introduced the hot cathode tube. The Coolidge tube caused a revolution in the type and design of generating equipment employed. In place of the induction coil, a high tension

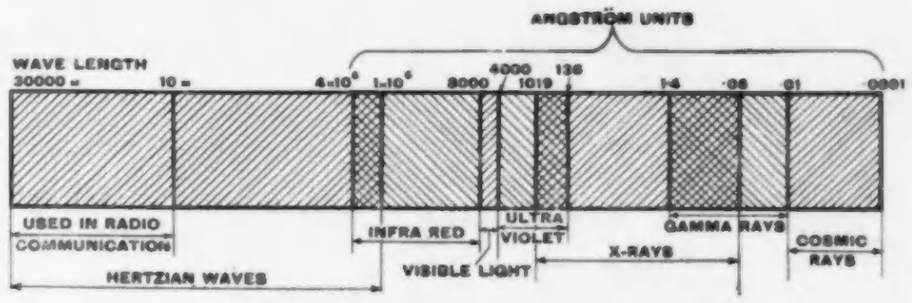


Fig. 1.—Illustrating the position of X-rays in the electro-magnetic spectrum.

transformer was used, either directly connected to the tube, or with some form of mechanical rectifier. The Coolidge tube, modified in various ways is still in use, but the mechanical rectifying equipment has given way to apparatus using thermionic valve rectifiers.

THE NATURE OF X-RAYS.

X-rays are a form of radiant energy of the same nature as light but of different wave-length; their position in the electro-magnetic spectrum is indicated in fig. 1. The wavelengths of X-rays are expressed in Angstrom units, one Angstrom Unit (A.U.) being equal to 1×10^{-8}cm. In medical practice the quality of X-radiation is not usually specified in terms of wavelength, but is defined by the peak voltage applied to X-ray tubes. It is also fairly common to speak of "soft" or "hard" radiation, a "soft" radiation being one of longer wavelength produced by a comparatively low voltage, such as 40 to 50 kV peak, and a "hard" radiation, a shorter one produced by a voltage of over 90 kV peak. These terms are not, of course, used in their everyday sense, but they are of service in that they indicate that a "hard" radiation is one which will penetrate more than a "soft" radiation.

PRODUCTION OF X-RAYS.

A simple X-ray tube is represented in fig. 2, and consists of a highly evacuated vessel into which are sealed two electrodes, the anode A and the

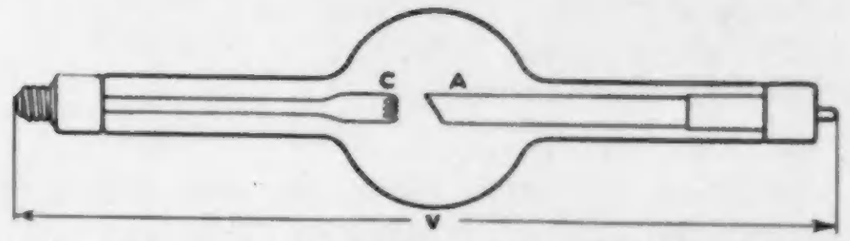


Fig. 2.—Diagrammatic representation of a simple X-ray tube.

cathode C. The cathode is a filament which is heated to incandescence, while the anode is usually a button of tungsten mounted on a copper rod.

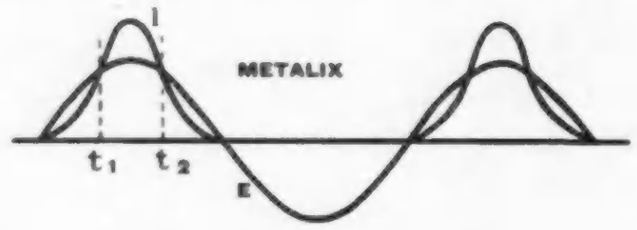
If a potential V is maintained between the two electrodes, the electrons emitted by the cathode will be accelerated by the electrostatic field, and will strike the anode with an energy eV, resulting in the production of X-rays at the anode, since X-rays are produced when rapidly moving electrons are stopped by matter. The anode emits X-rays, in the spectrum of which the shortest wavelength corresponds to a maximum frequency V max. given by

$$h\nu_{max.} = eV,$$

where h = Plank's Constant and e the fundamental electronic charge.

TYPES OF X-RAY TUBES.

The X-ray tube is the most important part of a radiological equipment and governs to a large extent the design of the generator. If an X-ray tube could



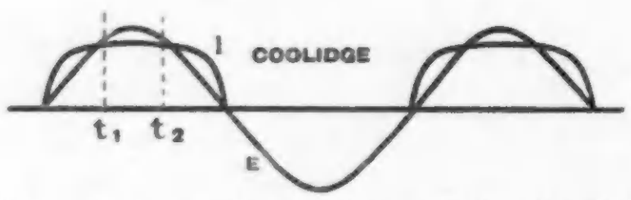


Fig. 3.—Comparison of wave-forms of a Coolidge and a Metalix tube.

be considered as a resistance load connected to a high voltage transformer, its design would be straightforward, but an X-ray tube possesses unilateral conductivity, and, furthermore, the current wave form is far from being sinusoidal for an applied sinusoidal voltage. In some types of tube the current wave is flat topped, whilst in other types the current wave is distinctly "peaky."

The variation in waveform between different types of tubes is best illustrated in fig. 3, which shows the waveform of a Coolidge and Metalix tube. It will be noted that the Metalix waveform is "peaky," the bulk of the current flowing at the peak voltage of the alternating current wave. In the case of the Coolidge tube the current is flat topped.

Modern X-ray tubes fall into four main categories :—

1. Glass type.
2. Self-protected type.
3. Shockproof type.
4. Research type.

Of these, research tubes are always specially designed for particular purposes and are not of commercial interest. They will consequently not be discussed in this article.

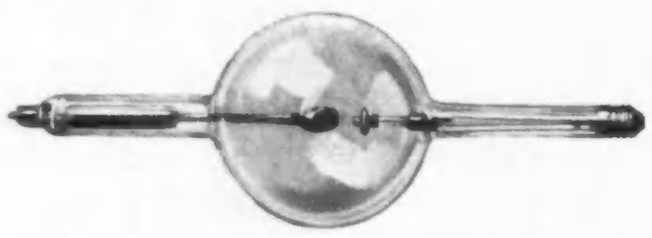


Fig. 4.—Coolidge "Universal" X-ray tube.

1. GLASS TUBES.

The first of the evacuated glass tubes is known as the Coolidge tube and is made in many different types, one being the "Universal" type illustrated in fig. 4.

The illustration gives a good idea of the construction of the tube, which consists essentially of a spherical glass chamber with two arms, one arm supporting the anode and the other the cathode structure. The anode consists of a shaped block of tungsten welded to the supporting stem, while the cathode consists of a spiral of tungsten wire mounted in a focussing shield.

A more recent type of glass tube is the "Muller." This tube possesses the great advantage of having a "line focus" instead of the round focus previously used. The advantage of the "line focus" can more easily be appreciated by reference to fig. 5.

The focal spot is made in the form of a narrow line, the length of which is several times the width, and on account of the small angle which the anode makes with the central ray in the direction of the X-ray beam, the line is seen as a small square.

The small "effective" size of focus gives very sharp definition in the resulting radiograph, whilst the "true" area makes it possible for the tube to withstand a heavy load.

2. SELF PROTECTED TUBE.

X-ray tubes of the Coolidge or Muller type possess the great disadvantage that apart from the useful beam, a great deal of unwanted radiation is given off. In order to protect the operator, these tubes have to be enclosed in lead lined boxes or lead glass shields which render the apparatus large and cumbersome. These objections have been overcome by the introduction of tubes which are designed to prevent any radiation emerging through the tube other than what is required.

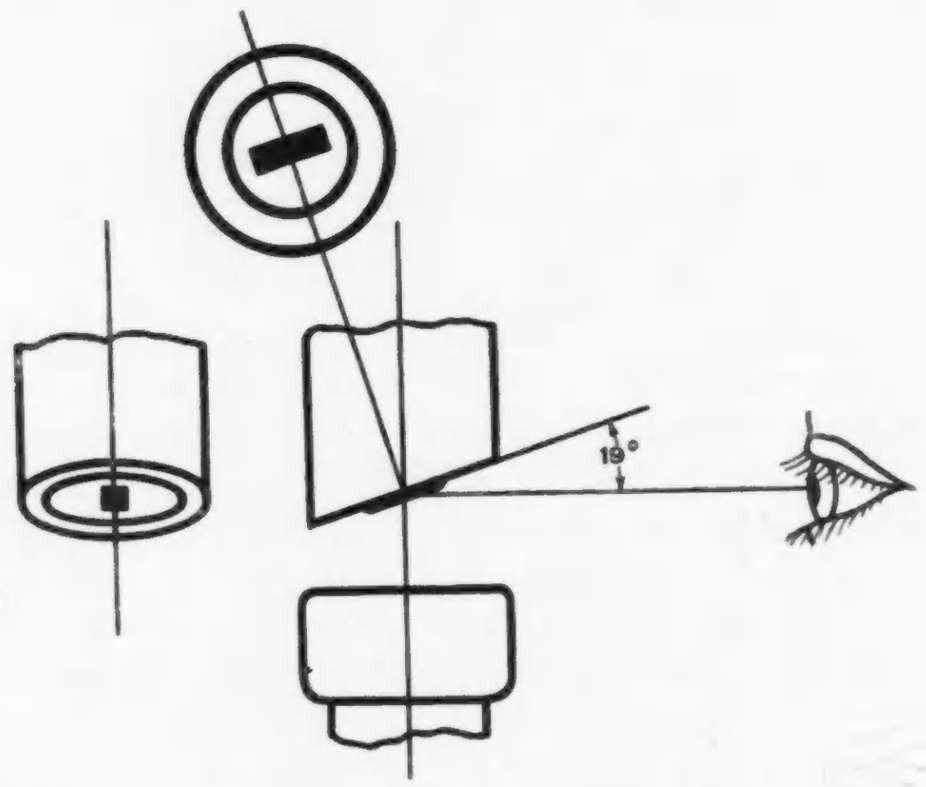


Fig. 5.—"Line focus" effect obtained with the Muller X-ray tube.

One of the first tubes of this type was the Metalix, the salient features of which are illustrated in diagram 6. The body of the tube is composed of a central cylinder of chrome-iron (1) to which

are directly sealed two re-entrant glass cylinders (4 and 5). One glass cylinder supports the anode (2) and the other supports the cathode (3). The central metal chamber is provided with a small glass window as a means of egress for the rays. As a further protection against unwanted radiation, the central cylinder is surrounded by a lead jacket (7) and rayproof bakelite cylinders (9) are mounted over the glass arms. The construction is completed by the metal clamp for supporting the tube, the radiator (10) for cooling purposes and the cathode cap (11) which carries the plug connection for the filament.

3. SHOCK-PROOF TUBES.

The most recent development in tube design is represented by tubes which are not only protected against X-radiation, but are also electrically shockproof. One which is typical is the "Metalix" Shockproof Tube which consists essentially of a Metalix tube enclosed in an earthed metal shield, the high tension supply being led in by rubber cables enclosed in an earthed metal braiding.

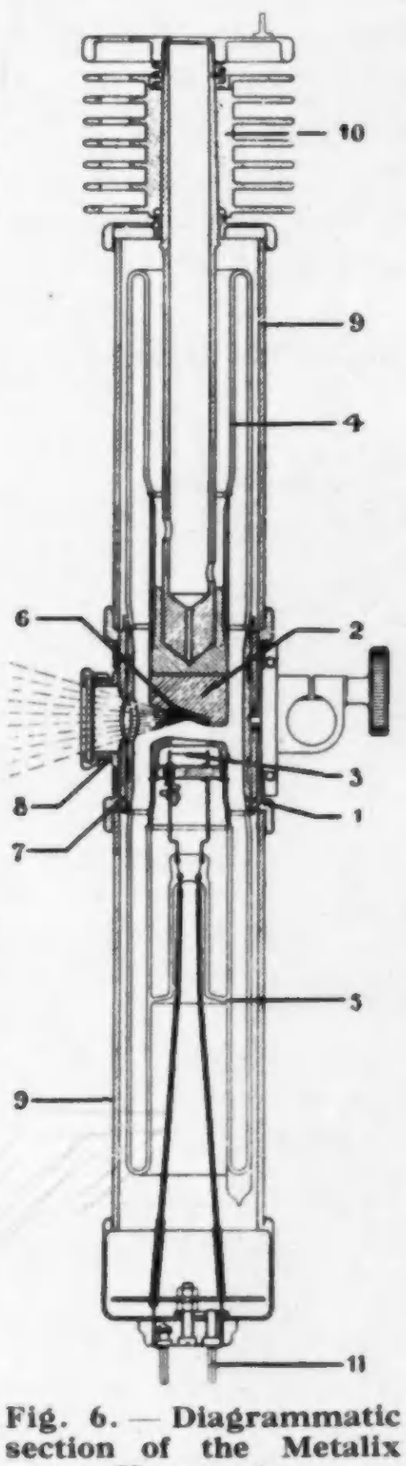


Fig. 6. — Diagrammatic section of the Metalix X-ray tube.

The application of a shockproof tube to X-ray medical equipment is shown in the illustration of the shockproof dental unit, fig. 7.

(A) *RADIOGRAPHIC EQUIPMENT.*

GENERATING EQUIPMENT.

The simplest form of X-ray equipment is known as "the self-rectified equipment," and consists essentially of a high tension transformer, insulated current transformer and control gear.

This equipment is usually designed to give a current of 30/50 milliamperes mean through the tube at a voltage of 80/90 kV peak.

A control panel is supplied with the apparatus and consists of a tapped auto-transformer to vary the voltage applied to the tube, a rheostat for controlling the tube filament current, a time-clock and contactor for making the exposure, together with a voltmeter and milliammeter.

The more usual types of self-rectified equipment are the dental equipment and what is known as the 30 milliampere equipment, the latter being used a great deal in small cottage hospitals, or mounted in a suitable trolley for ward use.

The self-rectified equipment is limited in its

Fig. 7.—Shockproof dental X-ray equipment.

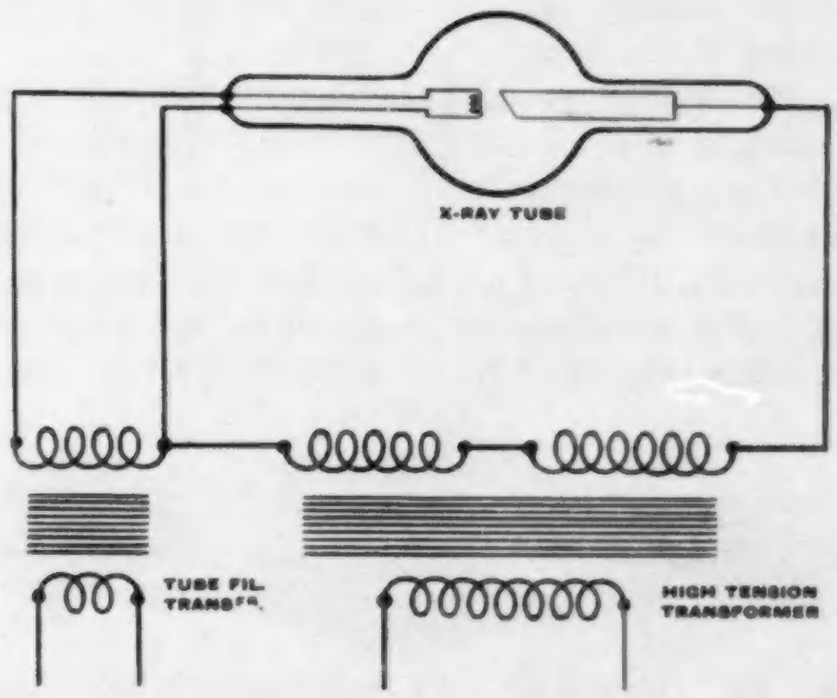


Fig. 8—Circuit diagram of simple form of X-ray equipment.

sphere of usefulness by the following two points :—

1. Inverse voltage.
2. Inverse current.

With regard to the inverse voltage, it must be born in mind that X-ray tubes are usually worked at their maximum rating and will not stand any

appreciable overloads. Since current is taken from the high tension transformer on one half of the alternating current wave only, the voltage drop on this half-wave will result in the working voltage

Fig. 9.—Simplest form of X-ray apparatus, known as the 30mA equipment.

being considerably lower than the voltage during the unloaded or "inverse" half-wave. It is this inverse voltage therefore that limits the working voltage on the tube.

Inverse current can be caused by the presence of a small amount of gas in the tube or by the anode becoming overheated and emitting electrons. The results are equally bad in either case and can result in the destruction of the tube. It is for these reasons that valve rectifiers are used, since not only does the valve prevent inverse current flowing, but it

Fig. 10.—The Osram EHT 3—a typical high voltage rectifier valve.

prevents the tube being subjected to a voltage greater than the working voltage.

VALVE RECTIFIER EQUIPMENT.

A typical high voltage rectifier valve is the Osram EHT.3, illustrated in fig. 10.

The simplest form of valve rectifier equipment is the single valve set, the general principle of which can be appreciated from fig. 11. A typical single valve equipment is illustrated in fig. 12.

While the single valve equipment represents a simple, reliable and comparatively cheap equipment, it suffers from limited output and poor voltage regulation. It must be appreciated that the important voltage in X-ray work is the peak voltage and not the R.M.S. value. In these circumstances it is the peak current and not the mean rectified current that limits the output of a transformer. For the half-wave or single valve apparatus the peak current is usually three to four times the mean current as read by the D.C. milliammeter used for current measurement. It is obvious that, by adopting full-wave rectification, the peak current is halved for the same mean value. In addition, a marked improvement is produced in the voltage regulation. This latter point is brought out clearly in the curve (fig. 13) which shows the voltage/current relationship for the same transformer connected in one case as a half-wave rectifier and in the other case as a full-wave rectifier using four valves.

For full-wave rectification four valves are used connected in the Bridge or Graetz circuit as shown in fig. 14.

A typical "four-valve equipment" is shown in

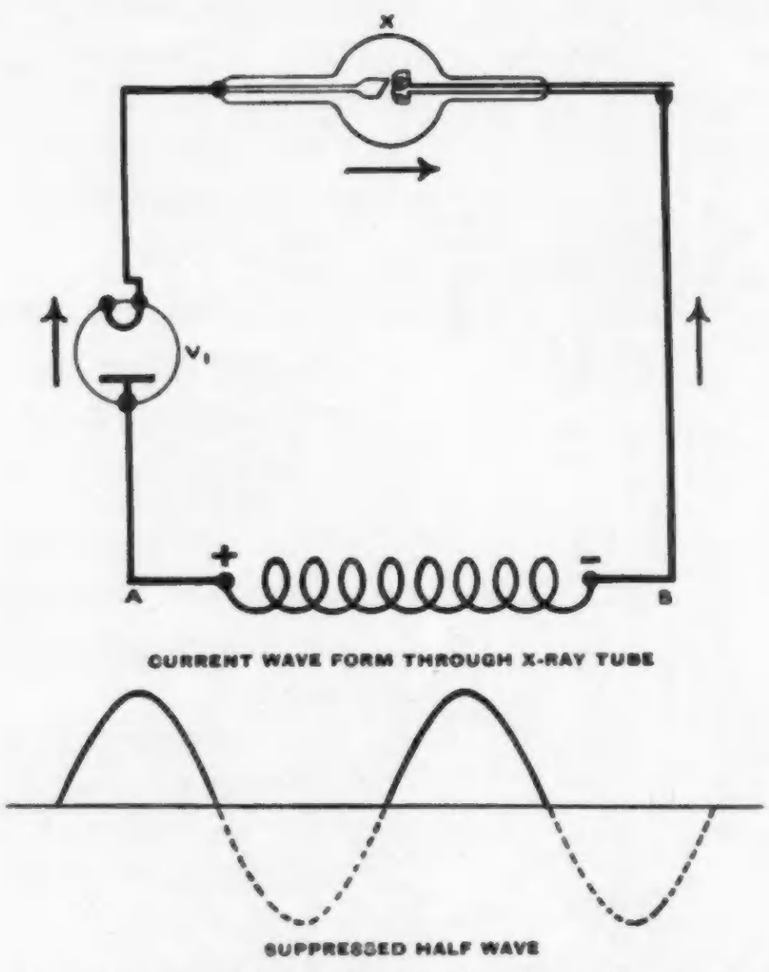


Fig. 11.—Circuit diagram of simplest form of valve rectified X-ray equipment.

fig. 15. Although full-wave rectification is a definite improvement on half-wave, there are still objections to be found. Since the voltage waveform is a rectified sine wave, current will flow through the X-ray tube at low voltage and give rise to a good deal of unwanted long wavelength radiation. The tube thus becomes heated to a degree disproportionate

with the useful radiation produced at the peak of the sine wave. This objection is overcome by the three phase, full wave system utilising six rectifiers as shown in fig. 16. Fig. 16A shows an actual six-valve set.

(*B*) *THERAPY EQUIPMENT.*

Apparatus for therapy or treatment purposes is called upon to perform a widely different function from radiographic apparatus. The latter is called upon to deliver a high current at comparatively low voltage for periods of the order of seconds only, whilst therapy equipment has to deliver a small current at high voltage continuously. In addition, it is preferable to smooth the rectified alternating current with condensers in order to obtain a high voltage direct current potential.

In order to keep the dimensions of the equipment within reasonable limits, it is usual to adopt some form of voltage doubling circuit, of which there are two main types.

The more inexpensive form of voltage doubling circuit is known as the "Villard" or "Pulsating Current" generator and consists essentially of a

Fig. 12.—Single valve half-wave rectified equipment having an output of 100 mA, 100 kV peak.

centre tapped high tension transformer, two high tension condensers, two rectifying valves and insulated current transformers for supplying the filament heating current of the rectifying valves and the X-ray tube. The components are connected up as fig. 17.

C_1 and C_2 are high voltage condensers. T is the high tension transformer and V_1 and V_2 are the rectifying valves. Assuming that the high tension transformer delivers 100 kV peak, *i.e.*, 50 kV peak from each section of the secondary, then on the positive half-wave the two condensers will each be charged to 50 kV (peak) via the valves.

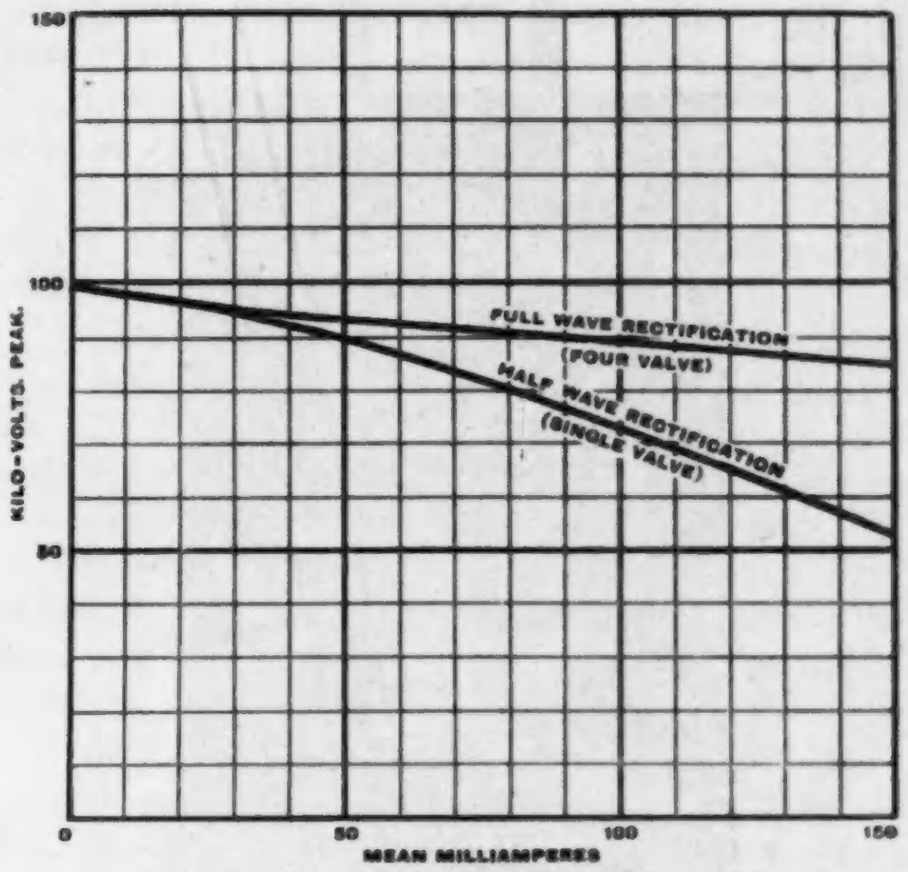
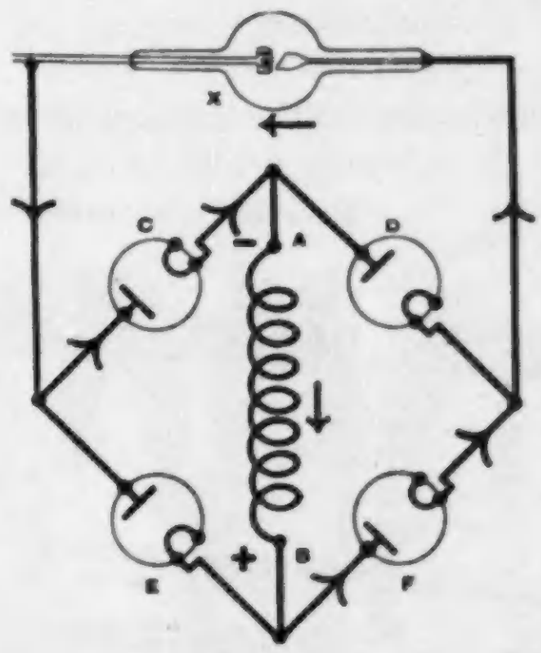


Fig. 13.—Voltage-current relationship for a transformer connected as a half-wave rectifier and as a full-wave rectifier using four valves.



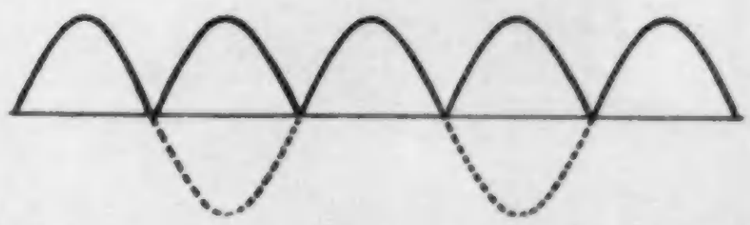


Fig. 14.—Circuit diagram of four-valve arrangement.

On the negative half-wave, the valves will become non-conducting and the voltage of the secondary will be added to the condenser voltage thus producing 200 kV peak on the X-ray tube. The current which then flows through the tube will be read by the

milliammeter inserted in the centre point of the transformer.

The effect of the two charged condensers, therefore, is to shift the zero of the alternating current wave to the peak of the negative half-wave, thus

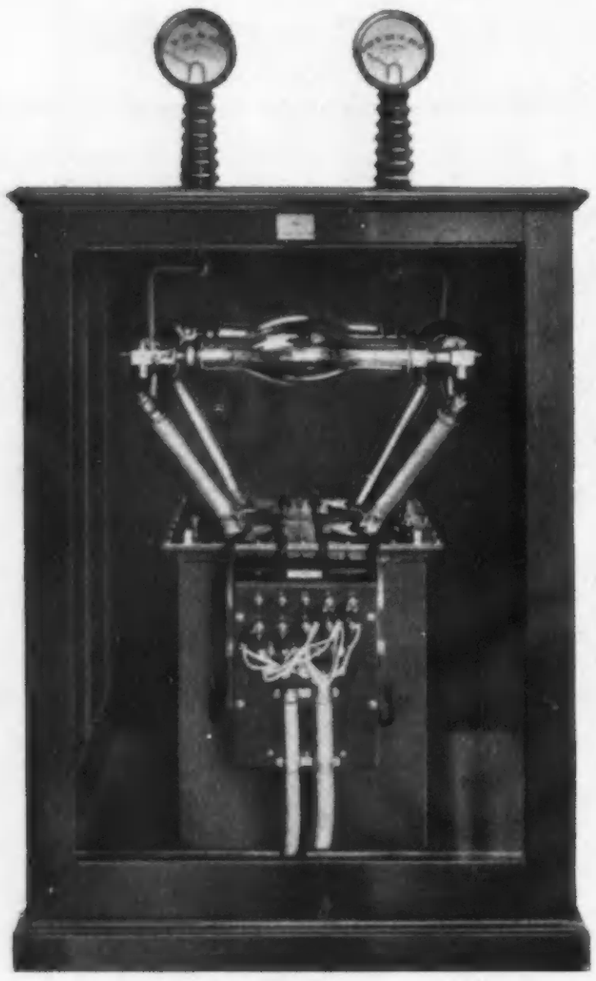


Fig. 15.—Four valve full-wave rectified equipment, having an output of 150 mA, 100 kV peak.

producing a unidirectional voltage of sinusoidal form.

The continuous current generator can best be understood by reference to figs. 18 and 19.

In fig. 18, "S" represents the secondary winding

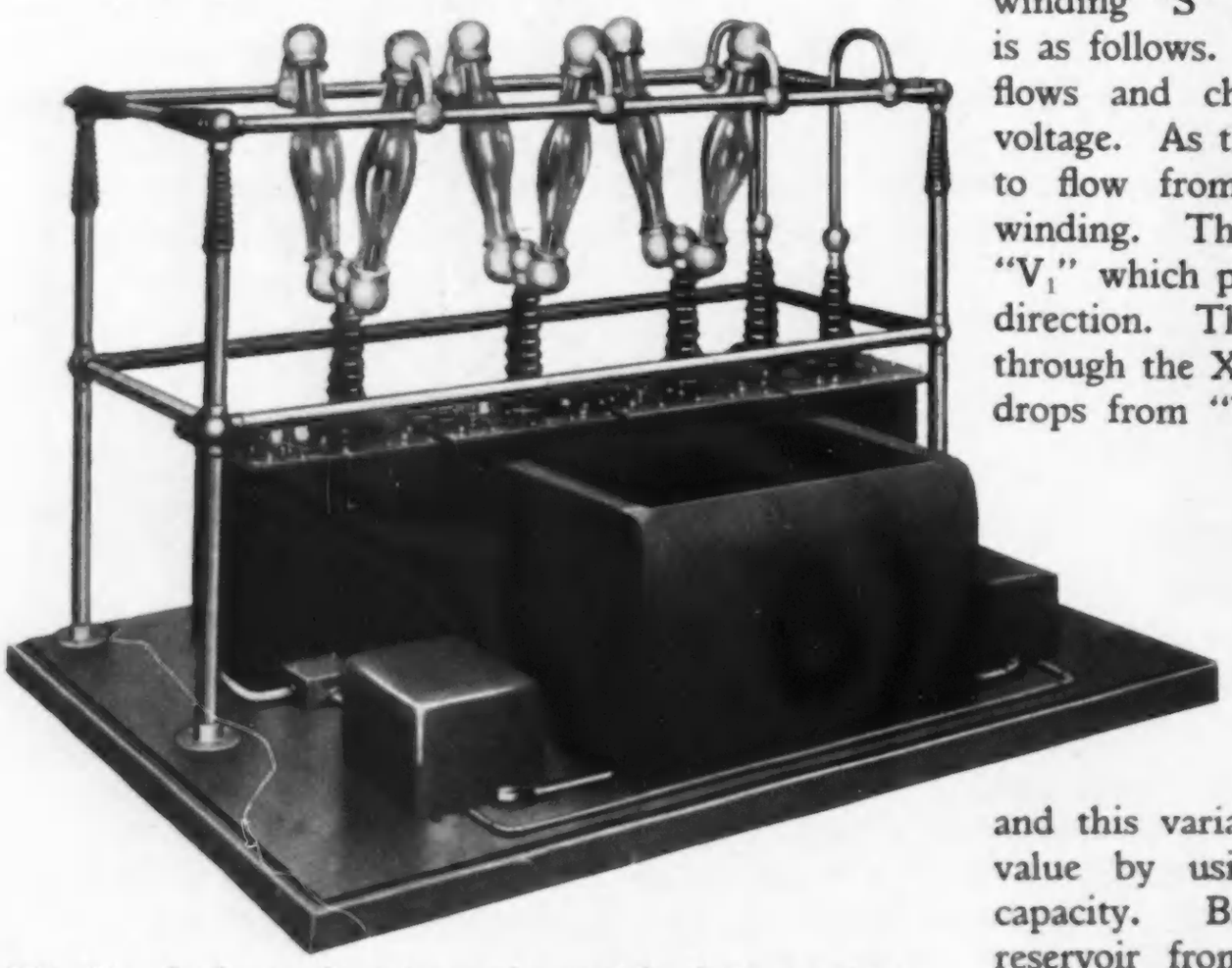


Fig. 16.—3-phase, six valve equipment, having an output of 300 mA at 80 kV peak.

of the high-tension transformer, "V_1" is a hot cathode rectifying valve, "C" is a condenser of large capacity and "X" is the X-ray tube. Fig. 19 is a curve showing the current wave forms, which

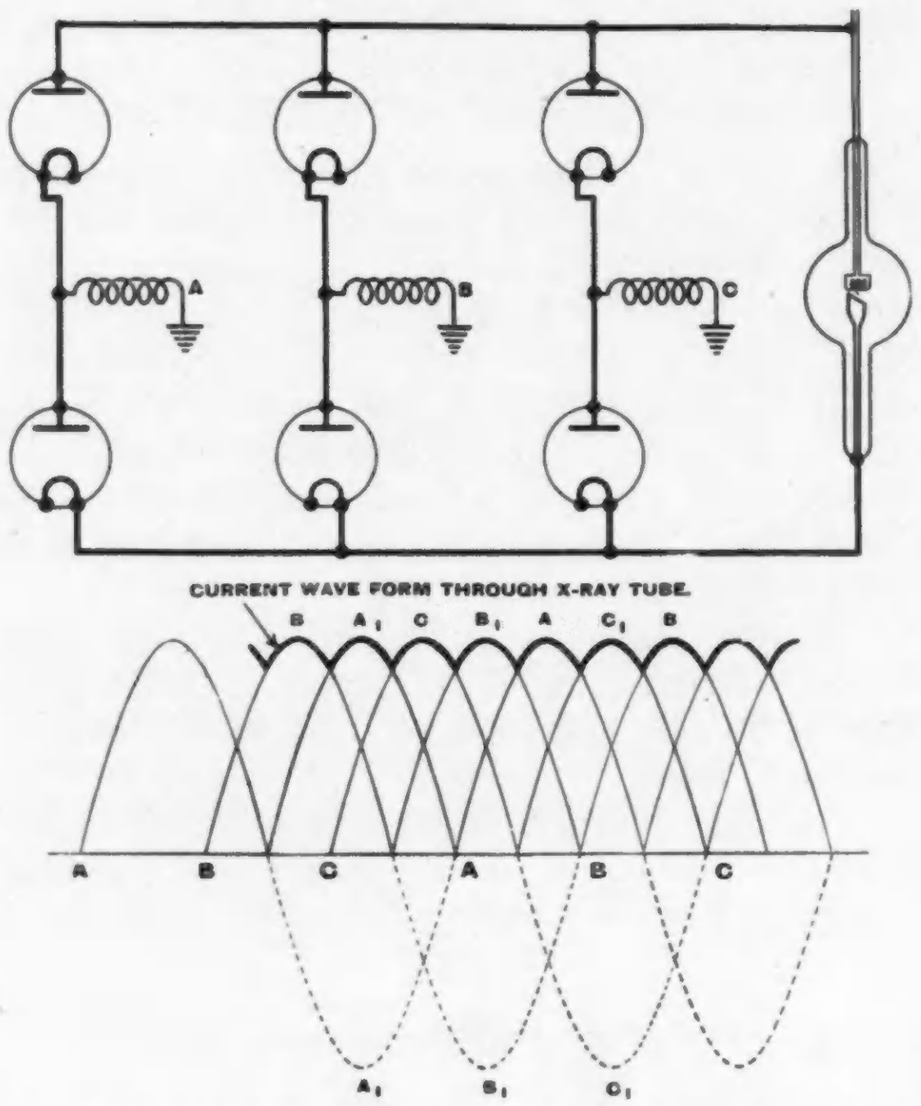


Fig. 16a.—Circuit diagram of six-valve equipment and resulting current wave form.

will assist in explaining the operation of the apparatus.

The sinusoidal curve A, B, C, D, E, F, G, H, represents the voltage generated in the secondary winding "S" (fig. 19) and the cycle of operations is as follows. As the voltage in "S" rises, current flows and charges the condenser "C" to peak voltage. As the voltage decreases the current tends to flow from the condenser, back through the winding. This tendency is checked by the valve "V_1" which prevents current passing in the reverse direction. The condenser, can however, discharge through the X-ray tube and in doing so the voltage drops from "V_1" to "V" (fig. 19). While this is taking place the voltage of the transformer secondary passes through the negative half-wave and recharges the condenser. Thus the voltage applied to the X-ray tube is represented by the curve B, L, F, M, H. This voltage varies only to the extent of the difference between "V" and "V_1" and this variation can be reduced to a very low value by using a condenser of sufficiently high capacity. Briefly stated, the condenser acts as a reservoir from which the tube is supplied with current, while at regular intervals the condenser

itself is supplied by the secondary winding of the transformer.

Using a single valve and single condenser as

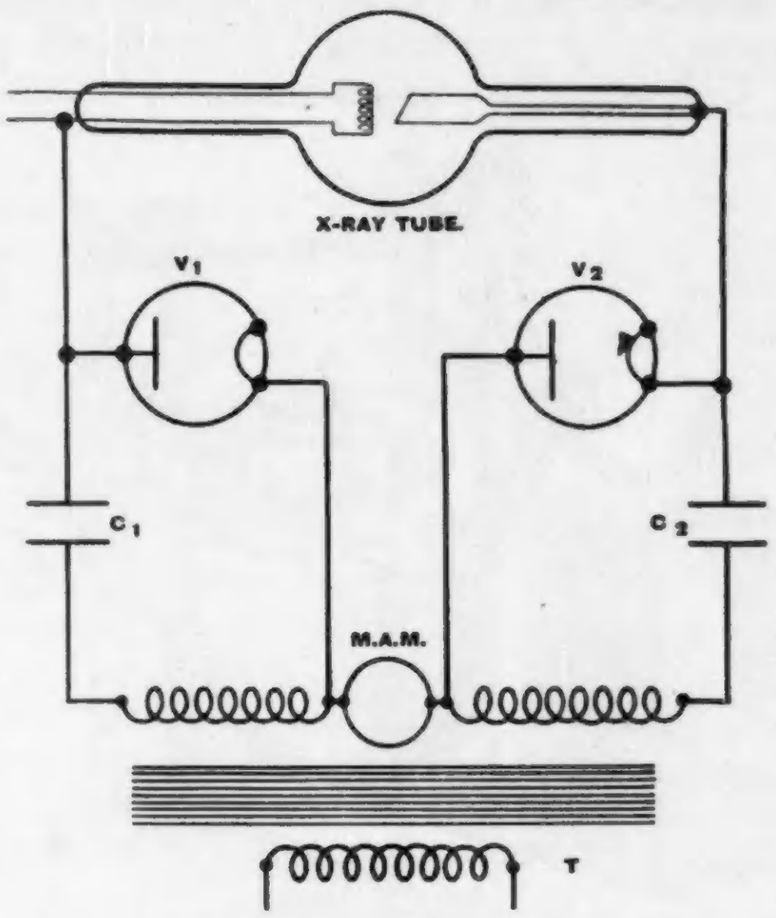


Fig. 17.—Circuit diagram of "Villard" generator.

shown in fig. 18, only one half of the alternating current wave is used, *i.e.* the positive half-wave; half the output of the transformer is therefore wasted and moreover, the voltage applied to the tube is only equal to the peak voltage of the winding "S." In actual practice two valves and two condensers are used, one valve and one condenser being charged by the positive half-wave and the other valve and condenser by the negative half-wave. By this means a voltage equal to double the peak voltage of the transformer is supplied to the tube terminals. This arrangement is shown diagrammatically in figs. 20 and 21. Fig. 20 shows the method of connection, and fig. 21 the voltage curves. The voltage applied to the X-ray tube is, in this case equal to "V_2" *i.e.*, double the peak voltage of the winding "S." Such equipment is illustrated in fig. 22.

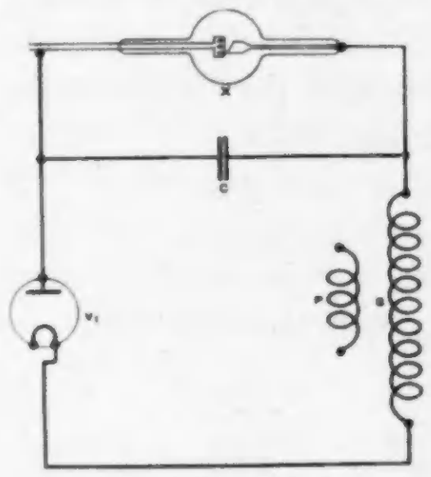


Fig. 18.—Continuous current generator.

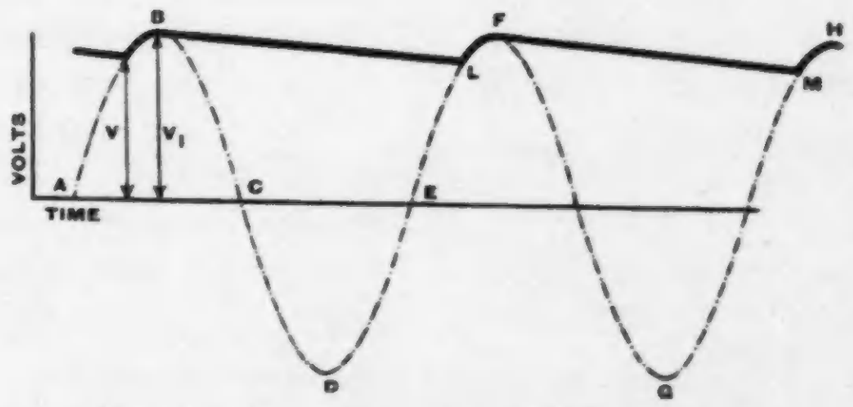


Fig. 19.—Wave-form of continuous current generator.

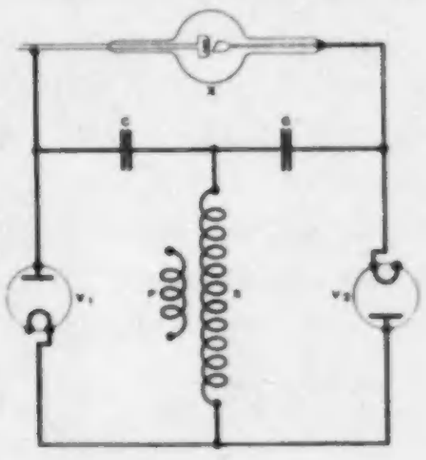


Fig. 20.—Method of connection to obtain double peak voltage of generator.

SHOCKPROOF THERAPY EQUIPMENT.

For a shockproof therapy equipment a high tension generator having small physical dimensions is essential and for this reason it was decided to use the "Villard" system which enables a small high tension transformer and small high tension condensers to be used.

The design of transformers for heating the X-ray tube filament and one valve filament presented considerable difficulty when it was attempted to make them of small dimensions. In the case of a 200 kilovolt equipment these transformers are called upon to withstand a tension of 100 kV each, this voltage being compounded of 50 kV direct current with a superimposed voltage of 50 kV alternating current.

A complete shockproof installation rated to work at 4 milliamperes 200 kilovolts is shown in fig. 23. The shockproof tube is supported on a specially designed gantry so that it can be freely moved in a horizontal, lateral and vertical direction and, furthermore, can be rotated round two axes at right angles to each other, thus making it possible for the emergent beam to be applied in any position or direction. Connection from the tube to the generator is made by means of flexible high tension cables.

The generator, which is seen in the back of fig. 23 is enclosed in a metal cabinet which has a safety switch fitted to the door so that the equipment cannot be operated without first closing the cabinet.

The generator unit consists of two parts:—

1. The generator proper.
2. The cooling pump.

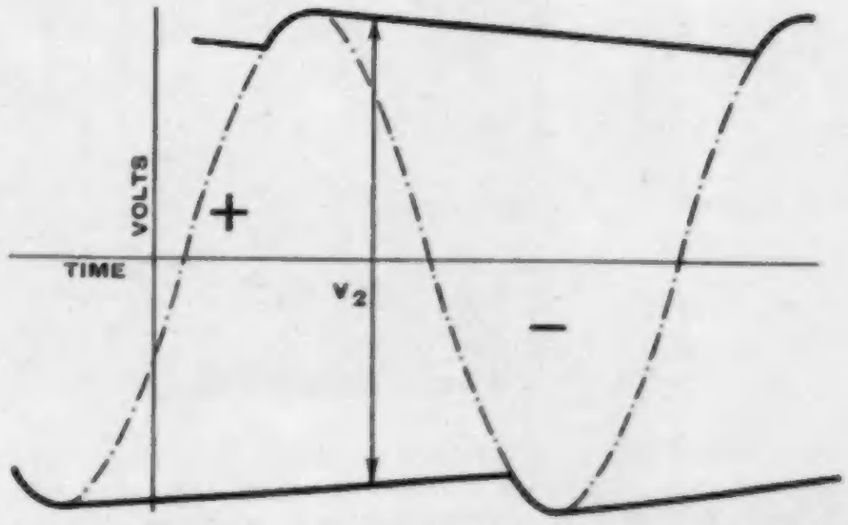


Fig. 21.—Wave-form obtained with arrangement shown in fig. 20.

The generator comprises a high tension transformer, two insulated current transformers, one earth potential current transformer and two high tension condensers. These are all oil-immersed in one tank, the high tension connections being brought up through bushings which form supports for the two rectifying valves. Great care has been taken to render every high tension point corona-less

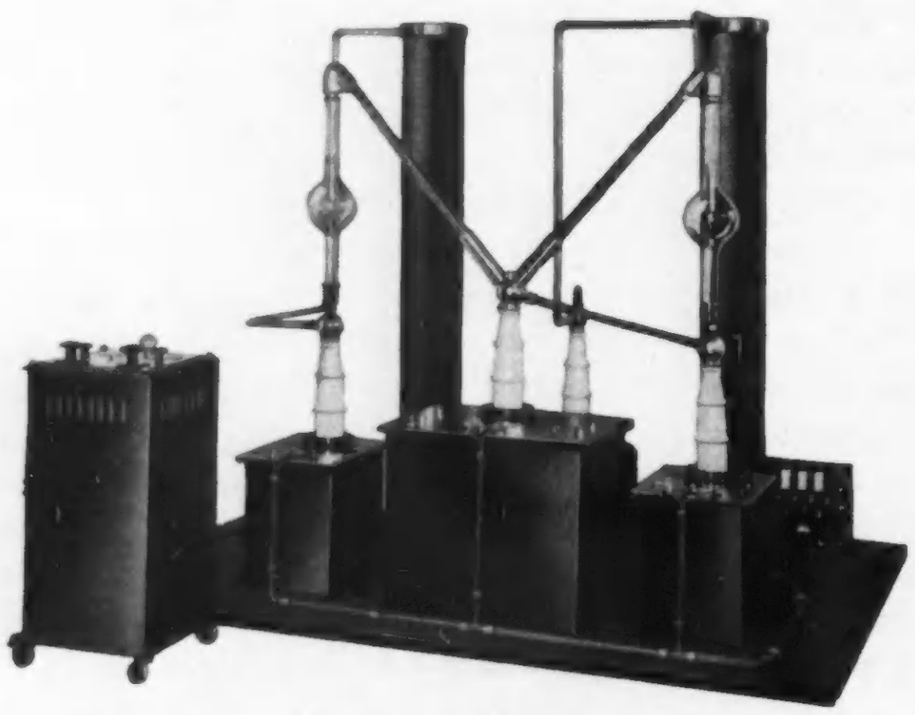


Fig. 22.—Constant potential generator, having an output of 10 mA at 200 kV direct current.

so that clearances could be reduced to a minimum. The cooling pump consists of a small induction motor, driving a water pump by means of an insulated shaft. The water is pumped through concentric tubes running through the centre of the anode cable, thence to a radiator which is cooled by a fan mounted on the pump shaft.

The overall dimensions of the cabinet containing the 200 kV generator and cooling pump are only 3ft. by 4ft. 6ins. by 3ft. 6ins. high.

Normally a "Villard" generator is at a disadvantage compared with the constant potential generator inasmuch as the "depth dose" is appreciably less. This is overcome in this equipment by utilising a

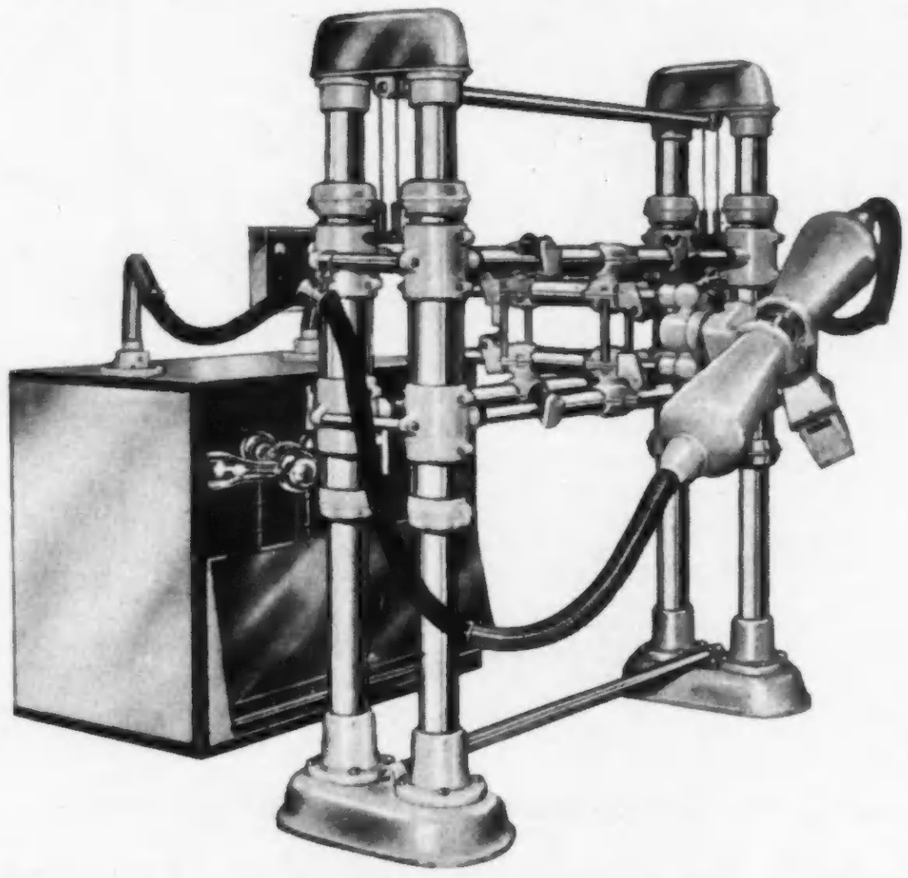


Fig. 23.—Shockproof equipment, giving 4 mA at 200 kV, pulsating current.

tube fitted with a third electrode and a biasing transformer. The effect of the arrangement is to prevent current flowing through the X-ray tube except at the peak of the voltage wave.

The result of this scheme is clearly shown in the two curves, fig. 24, which give the "depth dose" for different tube filtrations for a tube with biasing transformer and without biasing transformer.

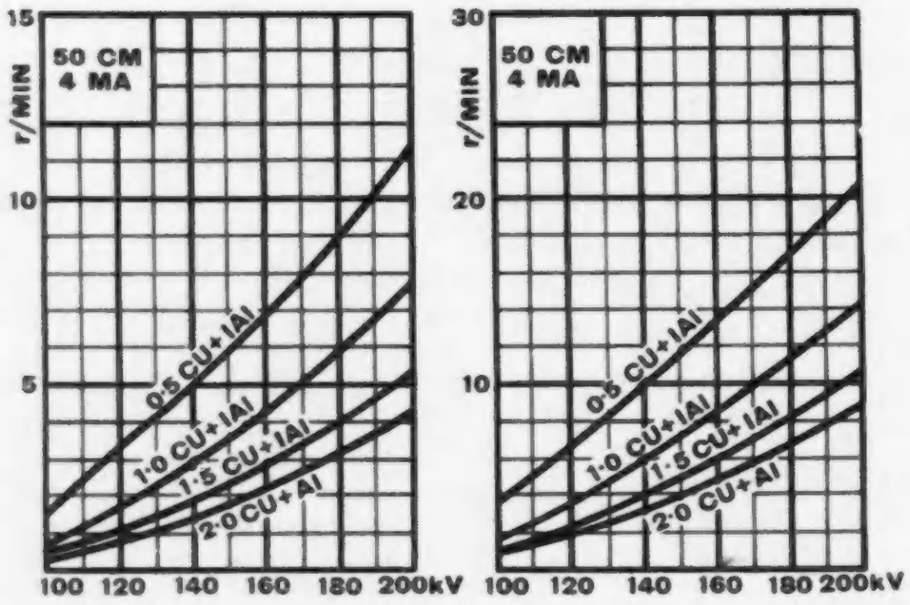


Fig. 24.—Curves showing "depth dose" for different tube filtrations for a tube with and without biasing transformer.

The Mercury Arc Rectifier.

By A. T. BARTLETT, B.A. (Cantab)., M.I.E.E.
Chief Development Engineer, Witton Engineering Works of The General Electric Co. Ltd.

In this article the author deals with the theory and application of the mercury arc rectifier.

As the subject is closely allied to that of gas discharge tubes and thermionic diode valves, it is recommended that reference be made to the two articles entitled "Gasfilled Relays," which appeared in the G.E.C. Journal, Vol. III, Nos. 2 and 3.

THE production of the world's demand for electrical energy is almost entirely by means of the power-driven alternator, and the distribution and consumption of this supply is very largely in the form of alternating current transmission lines and alternating current motors and other apparatus.

There are, however, conditions which can be best satisfied by the use of direct current, and so the demand for direct current is still considerable. Further, as direct current is favoured for traction schemes the demand for it may be expected to increase.

Rotating converting plant of many thousands of kilowatt capacity is in use, and has proved to be very satisfactory for pressures up to 700 or 800 volts. The tendency is, however, towards higher D.C. voltages, for which mercury arc rectifiers are more suitable. For this reason much study has been given to their development.

It is proposed in this article to give, in simple form, information concerning the theory and application of mercury arc rectifiers; also some points of their design and characteristics.

The thermionic diode valve and the gas discharge rectifier valves have, as regards their mode of operation, much in common with the mercury arc rectifier. In order to understand what goes on in the latter, it is proposed to consider first the ordinary wireless valve in the diode form. Such a valve consists of a filament (cathode) and a plate (anode), enclosed in a glass bulb evacuated to a very low pressure, as low perhaps as a thousand millionth of an atmosphere. The glass bulb therefore contains relatively few gas molecules.

If the filament is raised to a sufficiently high temperature, it will give off or emit negatively charged electrons, but all of these electrons do not necessarily escape completely from the filament.

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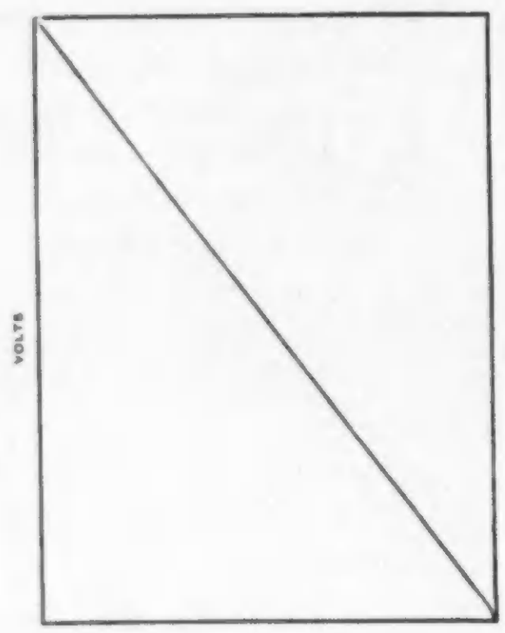
Fig. 1.—Three 1,500 kW G.E.C. automatically controlled mercury arc rectifiers, installed in Chiswick Park sub-station of the London Electric Railway. For the recent extensions to the western section of this railway a total of 13 15,000 kW automatically controlled mercury arc rectifiers, together with high and low tension switchgear, air-blast type transformer, high speed circuit breaker, etc., have been supplied by the G.E.C.

For example, if the anode is negatively charged by means of a battery, it is clear that the negative anode will repel any negative electrons, and any such electron which may leave the filament will be forced back into the filament and no current will flow between anode and filament. This phenomenon is in fact the simple explanation of the valve, or rectifying, action of electronic rectifiers. If, on the other hand the battery is connected so that the anode is slightly positively charged, only a fraction of the electrons which leave the filament would travel across the space to the anode.

To explain this, it is necessary to remember that electrons, being negative, tend to repel each other, and when a steady stream of electrons is passing from



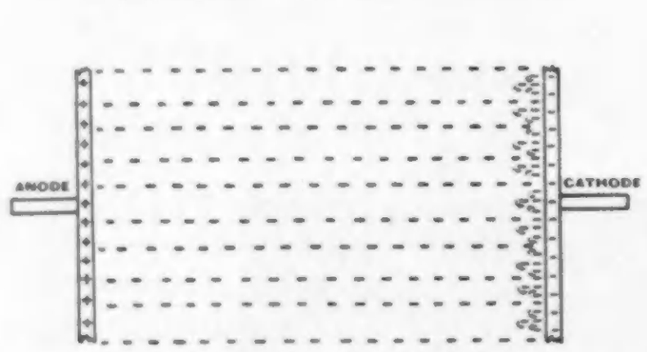


Fig. 2.—Diagrammatic representation of electronic movements and charges; the curve above shows drop in potential.

filament to anode, the whole space between filament and anode is negatively electrified; such negative electrification is termed a negative space charge, and its value is determined by the number of electrons per cubic centimetre.

Any electron leaving the filament may therefore be said to be attracted by the positive anode and repelled by the space charge formed by the electrons ahead of it on its way to the anode. Hence, in view of the low positive potential on the anode, only those electrons which are emitted at the higher velocities reach the anode; those with lower velocities are forced back into the filament.

The resistance offered by the space charge in vacuum valves, even with filaments running at very high temperatures, is so great that an anode potential of several thousand volts may be necessary to cause the whole of the electrons to flow to the anode. An attempt has been made in fig. 2 to indicate diagrammatically what has just been described.

If a D.C. difference of potential be gradually applied between the cold anode (positive) and the hot cathode (negative), it will be found that with given increments of voltage, the increments of current will gradually become less, as shown in fig. 3,

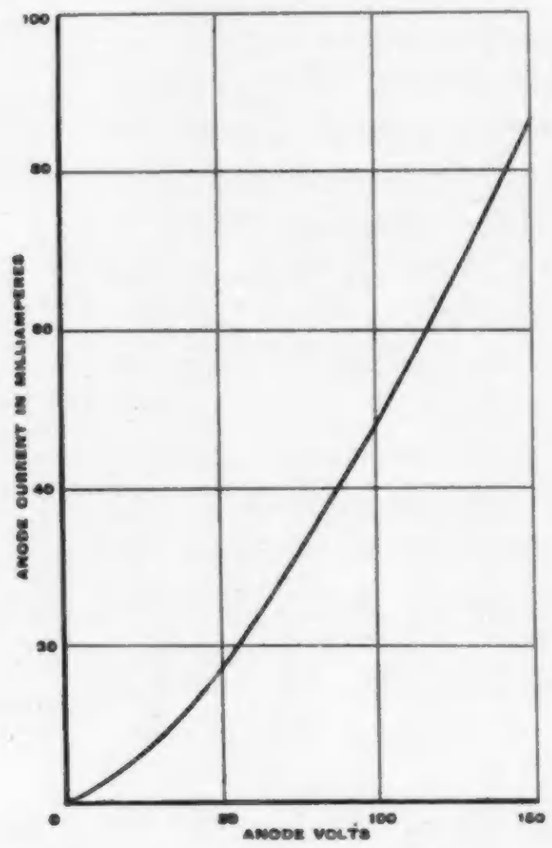


Fig. 3.—Typical characteristic of high vacuum rectifier.

and ultimately the current will be only slightly increased with large increments of voltage. The valve is then said to be saturated, or in other words, the emission of a thermionic valve is limited. Expressed in another way the flow of the current through the valve is due to the electrostatic field

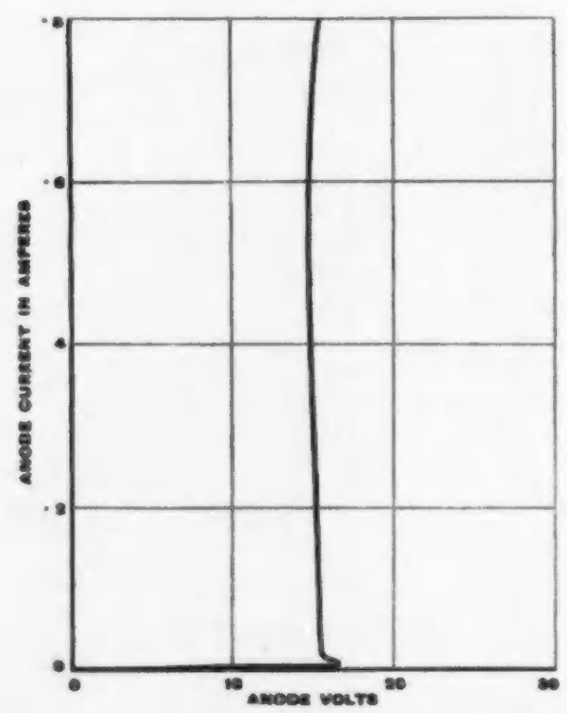


Fig. 4.—Typical characteristic of mercury vapour rectifier.

set up by the difference of potential applied between the cathode and anode, which field compels the electrons emitted by the cathode to travel to the anode. The value of current can in fact be stated

in terms of the number of electrons arriving at the anode in unit time.

The characteristic of a valve is profoundly changed, if, instead of the residual gas being air, certain other gases or mercury vapour are substituted. Attention will be confined to the latter.

The introduction of a small globule of mercury into the valve bulb before pumping, ensures after sealing off that the vacuum space will contain a number of mercury molecules which give rise to a vapour pressure depending upon the temperature of the bulb.

If the experiment of gradually applying a D.C. voltage is repeated, it will be found that for the first few volts, the valve will function in precisely the same way as though the mercury vapour were not present, but when the potential difference approaches about 10 or 12 volts, the bulb will become filled with a blue glow, and when in this condition a very slight further increase in voltage will cause the current to rise suddenly to a very high value; so high in fact may be this rise of current that it is necessary when carrying out the experiment to insert a limiting resistance in the circuit, in order to prevent the destruction of the sensitive coating of the filament. Fig. 4 shows the volt-to-current curve for a small glass bulb hot cathode mercury vapour rectifier.

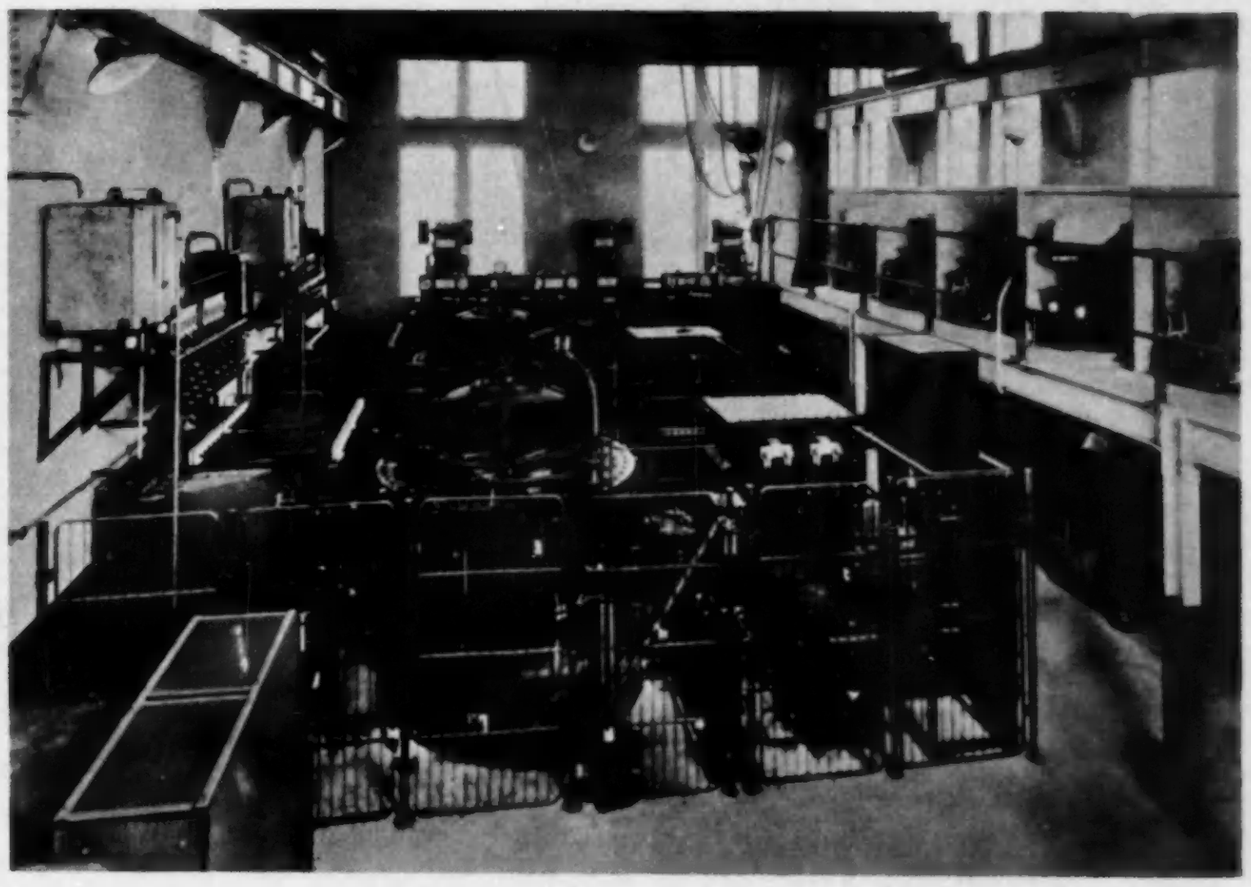


Fig. 6.—Two 1,200 kW G.E.C. mercury arc rectifiers installed in the Upney Lane sub-station of the L.M.S. Railway.

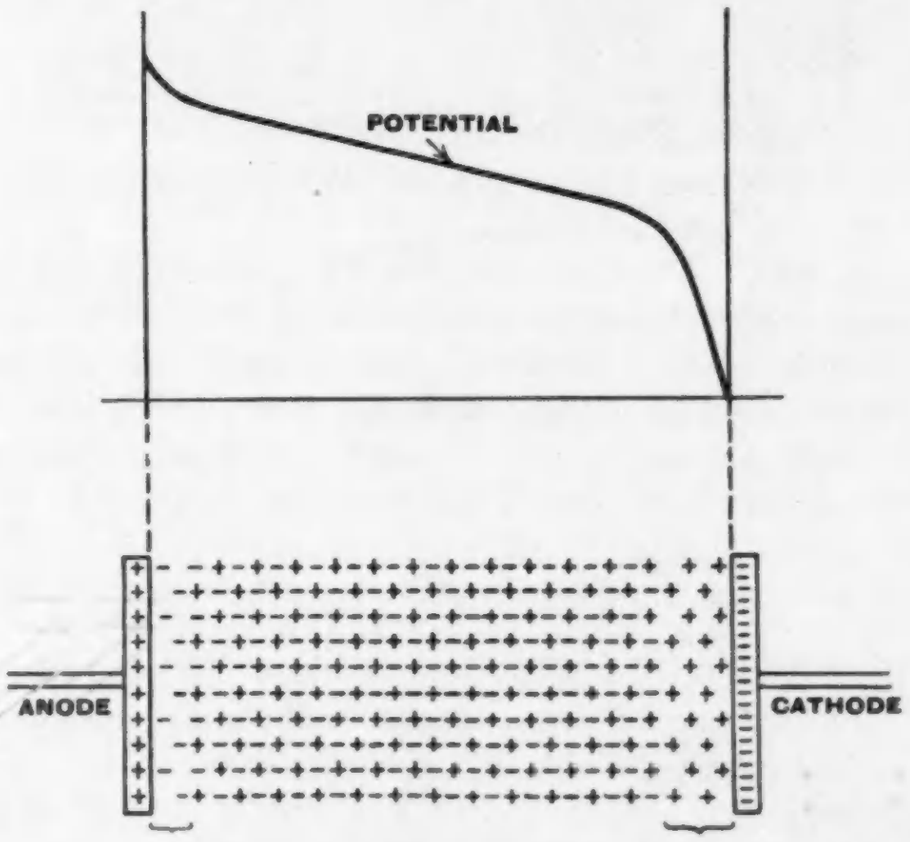


Fig. 5.—Diagrammatic representation of electron distribution in a rectifier when the mercury atoms have been ionised by electronic bombardment.

The startling difference between the two types of valve under consideration may be explained as follows:

In such a valve, any electron in passing from a point of low voltage to a point at a higher voltage, acquires a higher velocity, and with a voltage of 10 to 12 volts between cathode and anode, this velocity is sufficient to enable the electron when it collides with a mercury atom, to knock an electron from the atom, leaving the remaining portion of the atom (called an ion) with a positive charge. These new electrons also pass to the anode, while the heavier and therefore slower positive ions are attracted to the cathode.

The really important result of the electron collision with the mercury atoms is the neutralisation of the negative space charge by the positive ions, which is accompanied by the immediate decrease in the resistance of the "space" from a very high to a very low value.

Fig. 5 shows diagrammatically the average distribution of electron and ions after the voltage (10 or 12) on the rectifier have been raised sufficiently to ionise the mercury atoms by electronic bombardment. Hence, instead of thousands of volts being necessary to cause large numbers of the electrons to flow from cathode to anode in a vacuum rectifier, only 10 or 12 volts are required to cause a large current to flow through a mercury vapour rectifier.

In this type of rectifier the electron emission is in practice much larger and not nearly so limited as in vacuum rectifiers.

The next development is the substitution of a mercury pool cathode for the heated filament as the source of the electrons. If for the moment it is assumed there is a hot spot on the surface of the

mercury pool, the rectifier will behave in a similar way to the mercury rectifier with a hot filament, but there is now no reason to limit the current; the hot mercury will emit all the electrons necessary, and the mercury lost by evaporation will be condensed in the body of the rectifier and ultimately return to the pool. The only condition for the rectification of large currents is the maintenance of a hot spot on the mercury cathode. Fortunately, with rectifiers having more than one anode it is only necessary to produce a hot spot momentarily as after a current has once been started the hot spot is automatically maintained. This is due to the bombardment of the cathode spot by the ions which acquire a considerable amount of velocity and energy in passing through the voltage gradient on their way to the cathode.

A means of initially producing a hot spot is therefore all that is necessary to start a mercury pool rectifier, and the method of accomplishing this will be described later. For the remainder of this article, attention will be confined to mercury arc rectifiers with a mercury pool cathode.

In every rectifier there is a drop or loss of voltage. In large power rectifiers it may vary from about 20 to 35 volts, according to the design and the conditions of loading. The drop of voltage is not uniform and this want of uniformity is largely due to the presence of space charges close to the cathode and anode. Fig. 5 illustrates the space charges and how the fall in potential is distributed.

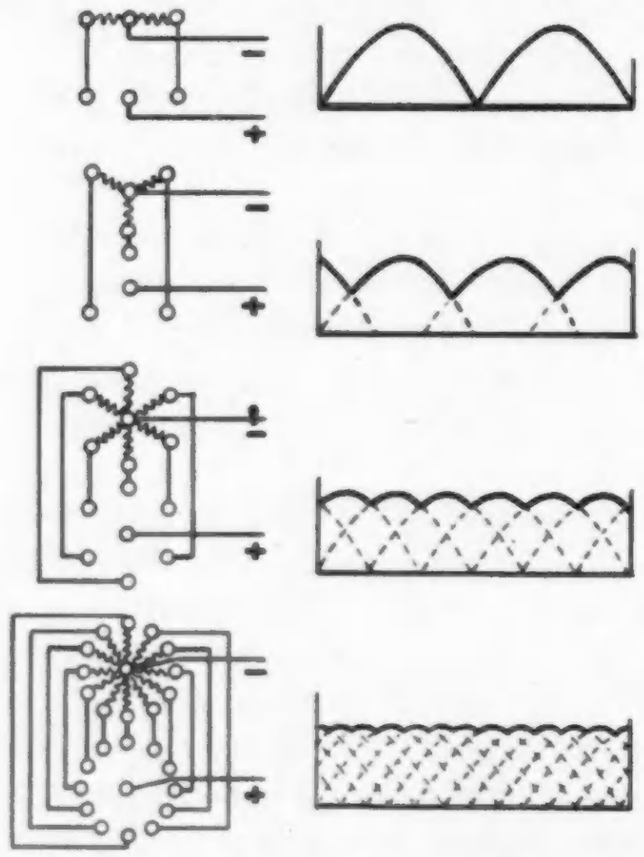


Fig. 7.—Diagrams of mercury arc rectifiers for single, three, six and twelve phase circuits, with wave forms showing decrease of ripple as the number of phases is increased.

In practice the voltage drop in a rectifier may be considered as being made up of three separate parts. First there is a drop of about 9 volts close to the cathode; secondly, there exists an effective drop of about 5 volts at the anode, while, thirdly, in the space between anode and cathode the voltage drop varies from 0.05 to 0.22 volts per cm. of the path length, depending also on the cross section of the path and the vapour pressure.

So far, a simple single-phase rectifier has been considered, but in heavy engineering, it is usual to

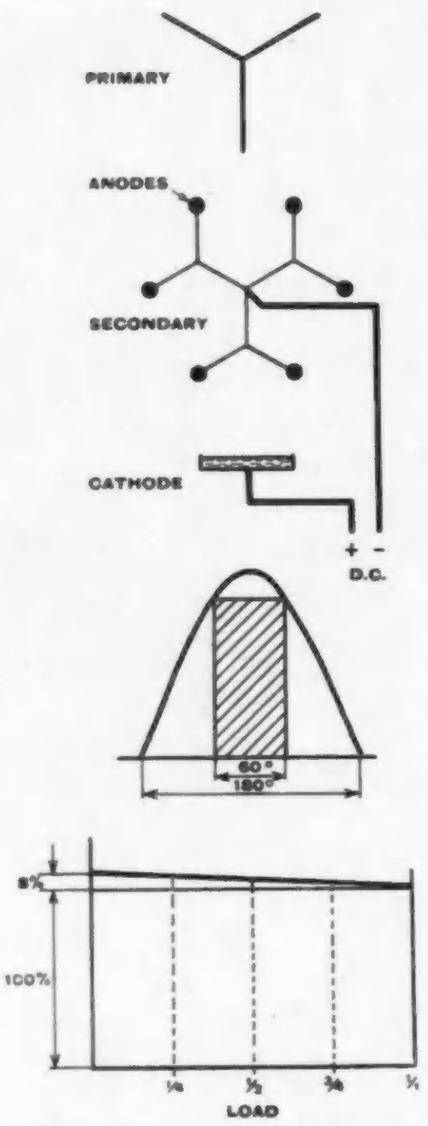


Fig. 8.—Six phase fork connections.

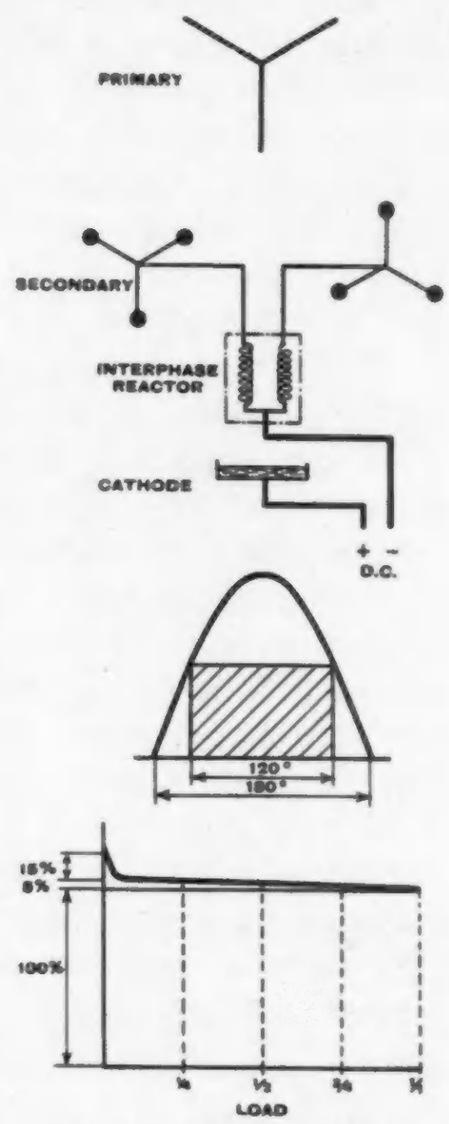


Fig. 9.—Double three phase connections with interphase reactor.

employ a number of phases, the six-phase rectifier being the most favoured.

The D.C. voltage or current from a rectifier can never be quite uniform, there being always a ripple present. Fig. 7 shows diagrammatically the ripple for four different phase numbers, from which it will be seen that the greater the number of phases, the less the ripple. It is advisable that the ripple shall be reasonably small; otherwise it may produce an objectionable hum in neighbouring telephone circuits.

IGNITION AND AUXILIARY ANODES.

The need for some means of starting a rectifier having a cold cathode has already been referred to. It must now be clear that the temperature of the cathode must be raised to the temperature at which electrons are more or less freely emitted, and with a mercury pool cathode a very small hot spot is sufficient. In practice, with metalclad rectifiers, it is usual to provide a "dipping rod," or electrode, which, by means of a solenoid is made to dip into the mercury pool and complete a low voltage local circuit. On the return of the dipping electrode to its normal position, an arc is produced between the rod and cathode. Electrons are emitted in sufficient

quantities to enable the main anodes to function and the main current to flow providing that the circuit is otherwise complete. Should however, the circuit at any time be interrupted, the cathode would lose its hot spot, and the starting or ignition process would have to be repeated. In practice this

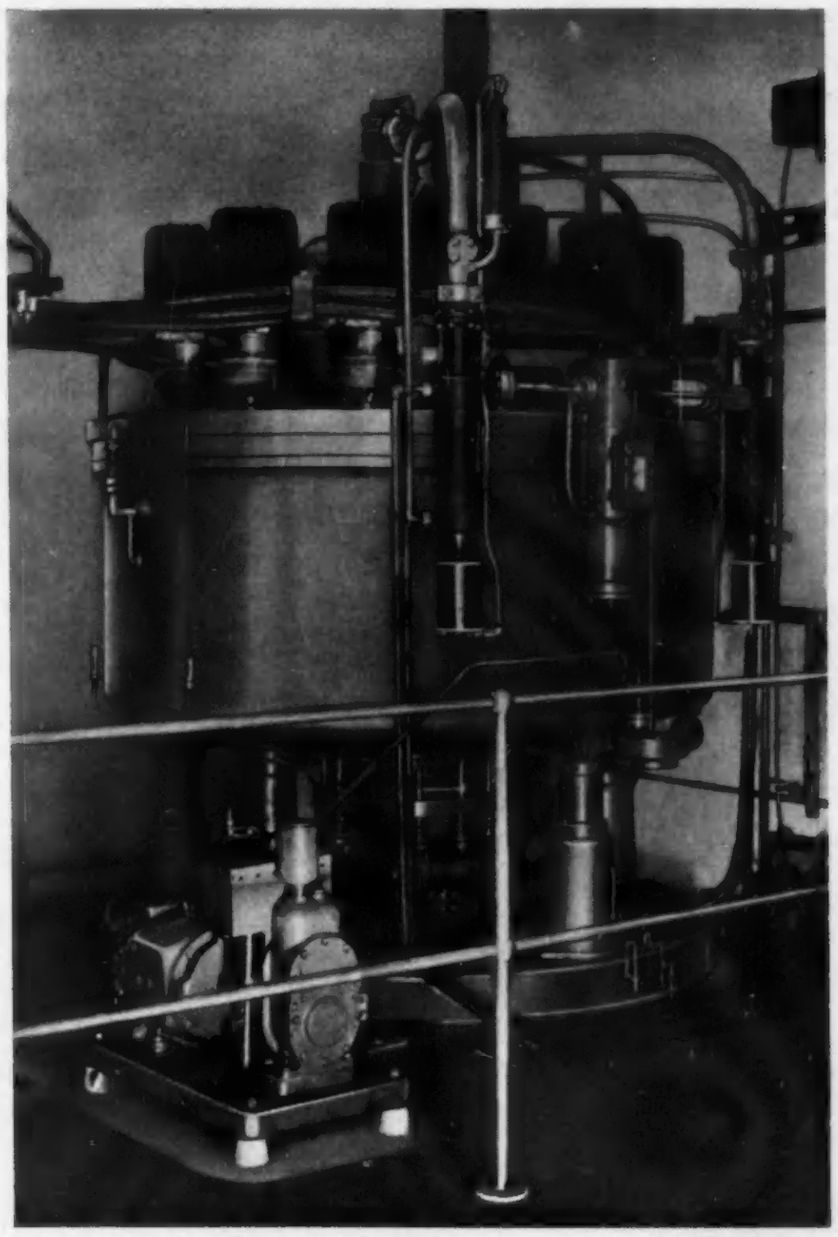


Fig. 10.—1,500 kW G.E.C. mercury arc rectifier installed in one of the Ilford Corporation sub-stations.

would be an impossible condition, and rectifiers are now fitted with two or more auxiliary anodes which are kept burning off a separate low voltage circuit.

The characteristics and design of steel tank mercury arc rectifiers will next be considered.

REGULATION.

The regulation of a rectifier is usually understood to be the difference in voltage of the rectifier from no-load to full load, including the regulation of the transformer and the voltage lost in any choke or smoothing coils. It is more often expressed as a percentage. The design and scheme of connections of the rectifier transformer are important factors in the regulation characteristics of a rectifier. There are a large number of schemes of connection available, but general practice has settled down to two main schemes, namely: (1) Six-phase fork connected secondary, and (2) Double three-phase with interphase reactor.

In the arrangement shown in fig. 8, the transformer is six-phase and the current, exclusive of overlap (which will be considered later), will flow for a time represented by 60 electrical degrees. With a transformer designed on economic lines, the voltage drop from no-load to full load will be about 8 per cent as shown.

In the double-three-phase arrangement, with interphase reactor, fig. 9, the effect of the introduction of the interphase reactor is little or nothing at low loads when the magnetising current of its core is very low. During this period the transformer delivers power as a six-phase unit, but when the magnetising current is sufficiently large to magnetise the interphase reactor core, the mode of operation changes from six-phase to double three-phase. The change is gradual, and is usually complete at a load of about 1 per cent of full load, the changeover involving no change in the ripple on the D.C. current. If the changeover or transition load value is taken as the point from which to compute the regulation, it will be seen from a comparison of figs. 8 and 9 that a great improvement has been effected by the adoption of an interphase reactor.

The explanation of the steep voltage drop, shown in fig. 9, which occurs during the change over from three to six-phase working is as follows. An examination of fig. 7 will show that the mean D.C. voltage must be lower with three-phase connection than with six-phase connection when a constant voltage is maintained on the primary of the transformer and it can be shown that this difference is approximately 15%.

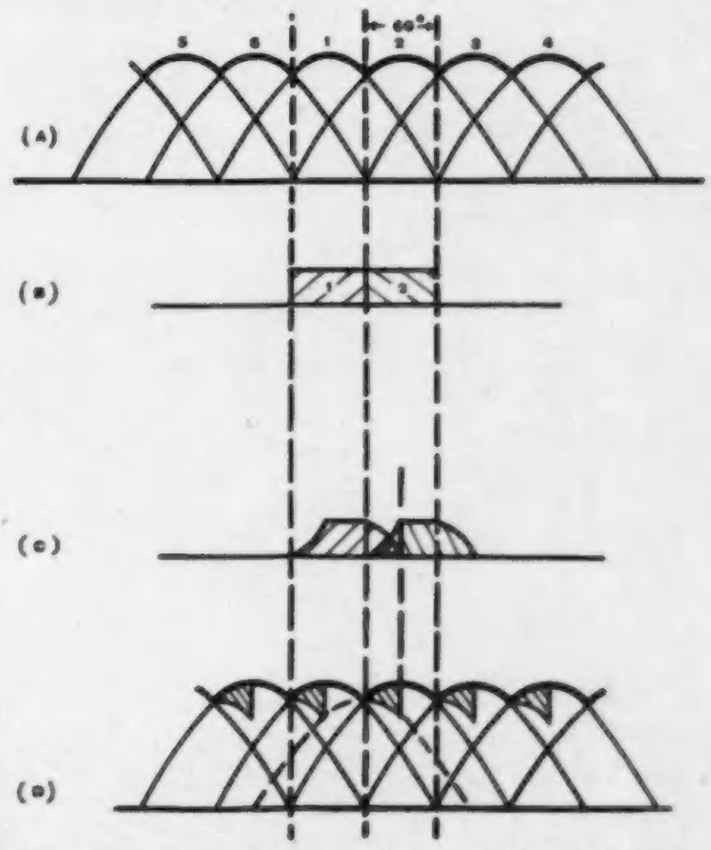


Fig. 11.—Current wave forms of six-phase mercury arc rectifier.

It is also shown in figs. 8 and 9 that with six-phase connection the current is carried by each anode for 60 degs. (neglecting overlap), but with three-phase connection the angle is 120 degs., with a much lower mean current per anode. Each of these differences influences the drop of voltage both in the rectifier itself and in the transformer.

The difficulty still remains that from actual zero load, the regulation is not better but worse, and that with a load of few lamps only on such a system, the lamps would burn out. Actually, in the case of large supply systems, this condition seldom arises, and where it may occur, it is usual automatically to switch in and out a resistance designed to absorb the transition load, when the normal load falls to a dangerously low value.

There are further factors outside the rectifier

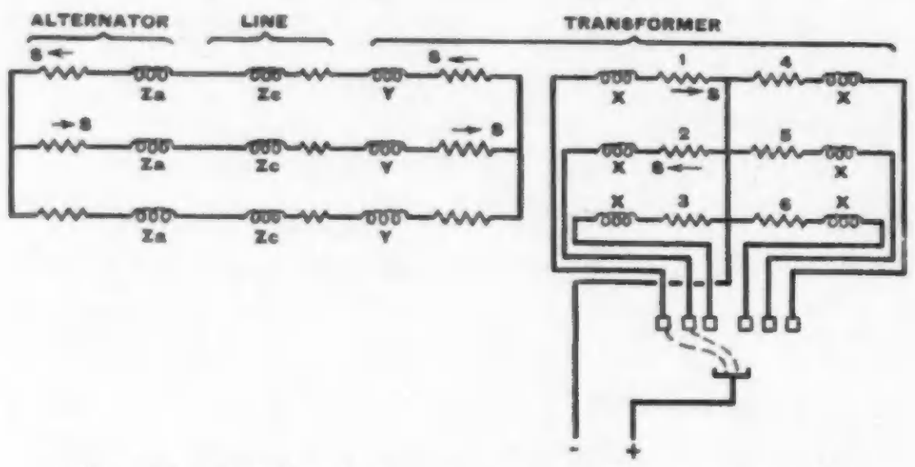


Fig. 12.—Illustrating reactances of power supply system to a rectifier.

which govern rectifier regulation. Neglecting for the moment the influence of the transformer and the scheme of connections, it will be assumed that some definite six-phase scheme and design has been selected. It would then appear that the regulation depends on the following, the first two of which are obvious :

(1). The losses in the rectifier itself, which may be expressed as a voltage drop.

(2). The copper losses in the transformer resulting in a drop of D.C. output proportional to the load.

(3). The effect of commutation which is not so apparent, and which will require further explanation.

Assuming the case of a six-phase transformer connected to a six-anode rectifier, the form of the voltages supplied to the anodes of the rectifier are sine waves displaced by 60 electrical degrees (see fig. 11A). It follows that each anode will carry current for the time represented by 60 degs., as only that anode with the highest positive voltage with respect to the cathode is able to carry current, the transfer of current from one anode to the succeeding anode occurring at the moment of intersection of the respective voltage waves.

If commutation could take place instantaneously, rectangular current waves would result, as shown in fig. 11B, but owing to the inevitable reactance in the circuit, instantaneous commutation is impossible. In practice, a gradual increase and decrease in the current of each anode must take place, with the result that the anode current wave must take the form shown in fig. 11C. In practice, therefore, two anodes actually carry current simultaneously during the time of commutation, a period to which the term "overlap" (usually expressed in electrical degrees) has been applied.

Two conclusions can be derived from the presence of overlap.

(1). During the time of commutation, both anodes must have the same potential with respect to the cathode.

(2). A short circuit therefore exists between both anodes during the overlap, which results in an alternating component in the circuit of anodes 1 and 2, superimposed on the D.C. current opposing that of anode 1, and adding D.C. current to anode 2.

The resulting D.C. ripple will no longer consist of crests of sine waves, as in fig. 11A, but will be of the form shown in fig. 11D, and the average value of the D.C. voltage will be reduced by the shaded areas. This distortion occurs also in the A.C. wave form. It is clear therefore that distortion in the A.C. wave form results in a drop in the D.C. voltage, and that the greater the time of overlap, the greater is the D.C. voltage drop.

Since the value of the short circuit current is mainly limited by the reactance in the circuit, it follows that the larger this reactance, the greater will be the overlap and wave distortion, and the greater the D.C. voltage drop of the rectifier.

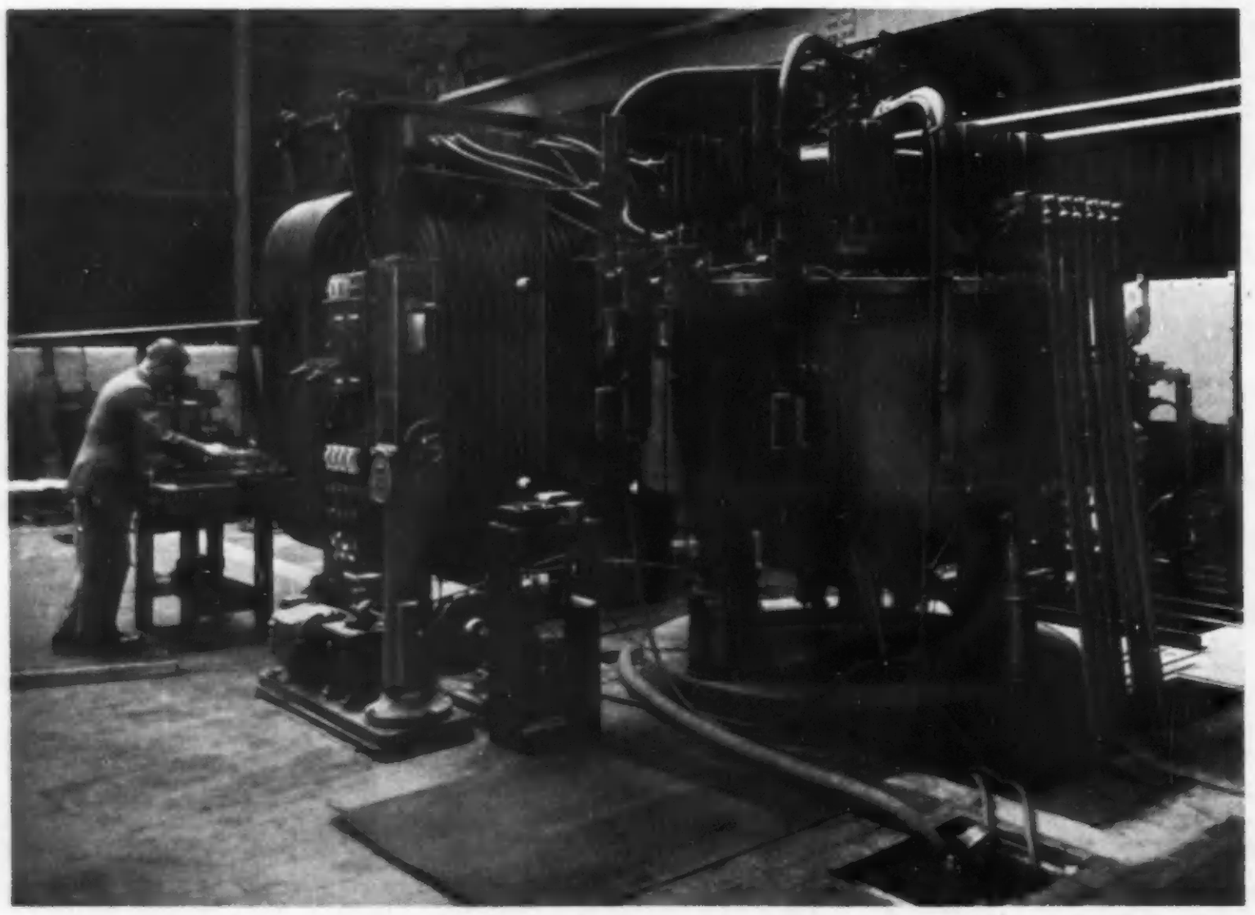


Fig. 13.—1,500 kW mercury arc rectifier on test in Witton Engineering Works.

Having now shown the influence of reactance on the regulation of rectifiers, it is of importance to know how this reactance is distributed in the circuits, and to what extent the various reactances affect the regulation.

It is generally assumed that the leakage flux of the rectifier transformer forms the most important part of the total reactance in circuit. With a transformer of a good and economical design, the D.C. voltage drop due to leakage flux will be about 2½ per cent with a D.C. working pressure of 630 volts, which is the basis on which these remarks are made. Adding to this the copper losses and the increase in the voltage drop in the rectifier arc from no-load to full load, and also the voltage drop in the choke coil usually provided for the purpose of smoothing the D.C. current, it is found that the closest inherent regulation which can be economically obtained is about 4 per cent.

There are, however, cases where the transformer reactance is not the only important reactance. Fig. 12 shows that the short circuit currents flowing in the transformer windings during the overlap must also flow through the feeder cables and the alternator windings. With a relatively small alternator supplying power to a rectifier through relatively long feeders, it is quite possible that the reactances thus added may increase the regulation from the 4 per cent already mentioned to at least 8 per cent. This is an exceptional case, but it is quoted in order to show that without full knowledge of the supply conditions it is impossible to guarantee the working regulation of a rectifier plant and it is only possible to give the inherent regulation.

Under usual supply conditions, a reasonable regulation is about 5 per cent at 630 volts D.C.

Apart from the difficulty of obtaining a closer regulation, it is probably unwise to aim at a better figure owing to the extremely large currents which may occur on short circuit or back fire and which would involve the use of larger and more expensive A.C. and D.C. switchgear.

EFFICIENCY.

It has already been stated that the voltage drop in a rectifier is about 20 to 35 volts. It therefore follows that with a low voltage of say 100 volts D.C., the losses must be at least 20 to 35 per cent (excluding transformer and other losses) involving a very low efficiency. At 600 to 800 volts D.C., however, the losses are relatively low, and the efficiency of a well-designed rectifier plant about equals that of a rotary converter at full load, and is higher at low loads. Here, it may be remarked that whereas the losses in ordinary converters vary more nearly as the square of the current, in rectifier plants they vary approximately directly with the current. The variation of efficiency with the D.C. voltage is shown in fig. 14. Transformer and auxiliary losses are included. The efficiencies of a 2,000 amp. 630-volt rotary converter and rectifier, both designed to the same specification, are given in fig. 15.

Where converting plants are required to run for long periods on low loads, as often occurs in traction

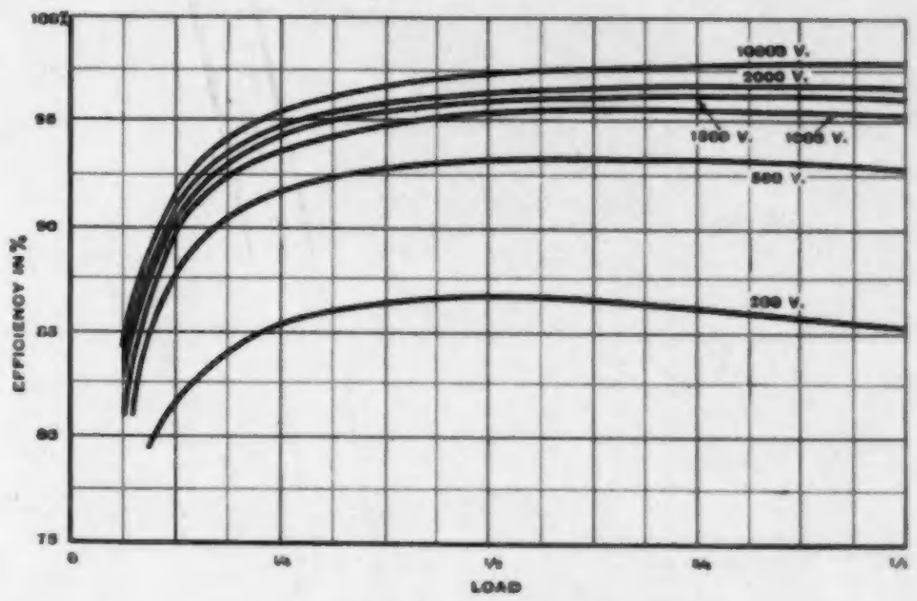


Fig. 14.—Efficiencies of rectifier at various D.C. voltages.

practice, the *all-day* efficiency of rectifiers may be considerably in excess of that obtained with rotating converting plant owing to their high efficiency on low loads.

OVERLOAD CAPACITY.

Fundamentally, and contrary to the usual statements, rectifiers have little or no overload capacity,

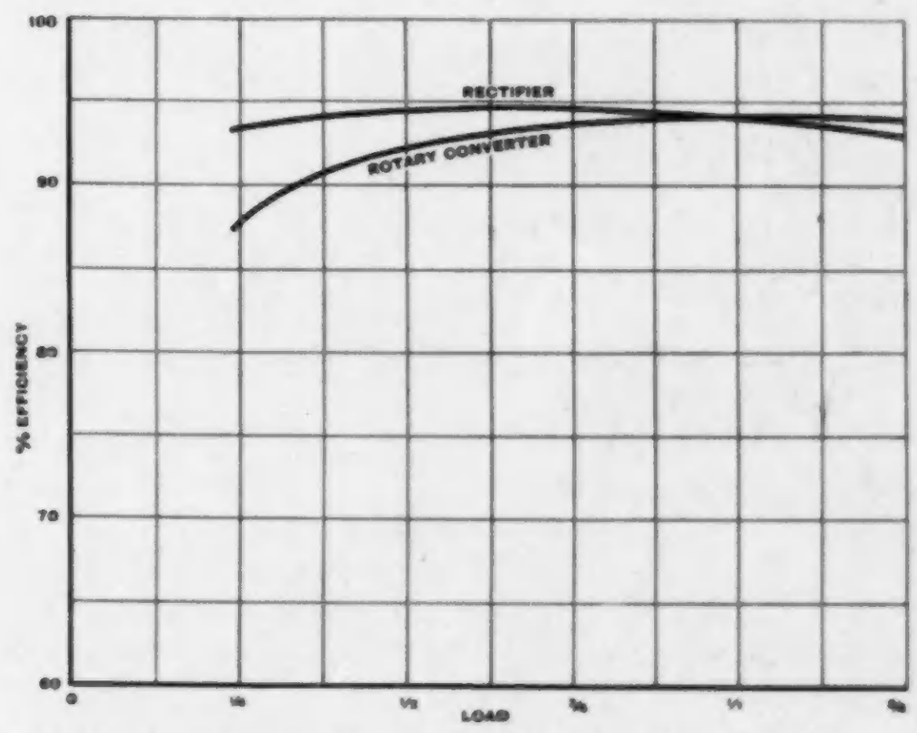


Fig. 15.—Comparisons of efficiences of 2,000 amp. rotary converter and rectifier.

except for anything other than momentary overloads; the reason being that they have little or no thermal capacity whilst rotating converters have considerable thermal capacity. The engineer, however, has so long been accustomed to think in terms of overload capacity, that it has been considered advisable to rate rectifiers on much the same lines as rotating

converters. It is now usual therefore, to guarantee the following overloads :

50 per cent overload for one hour.

200 per cent overload momentarily.

As regards momentary overloads, rectifiers are definitely superior to any machine with commutators, and their overload capabilities are shown in the chart, fig. 16, which is a reproduction of a current chart obtained in service on a traction system.

On the test bed, rectifiers have been short-circuited many times in quick succession with

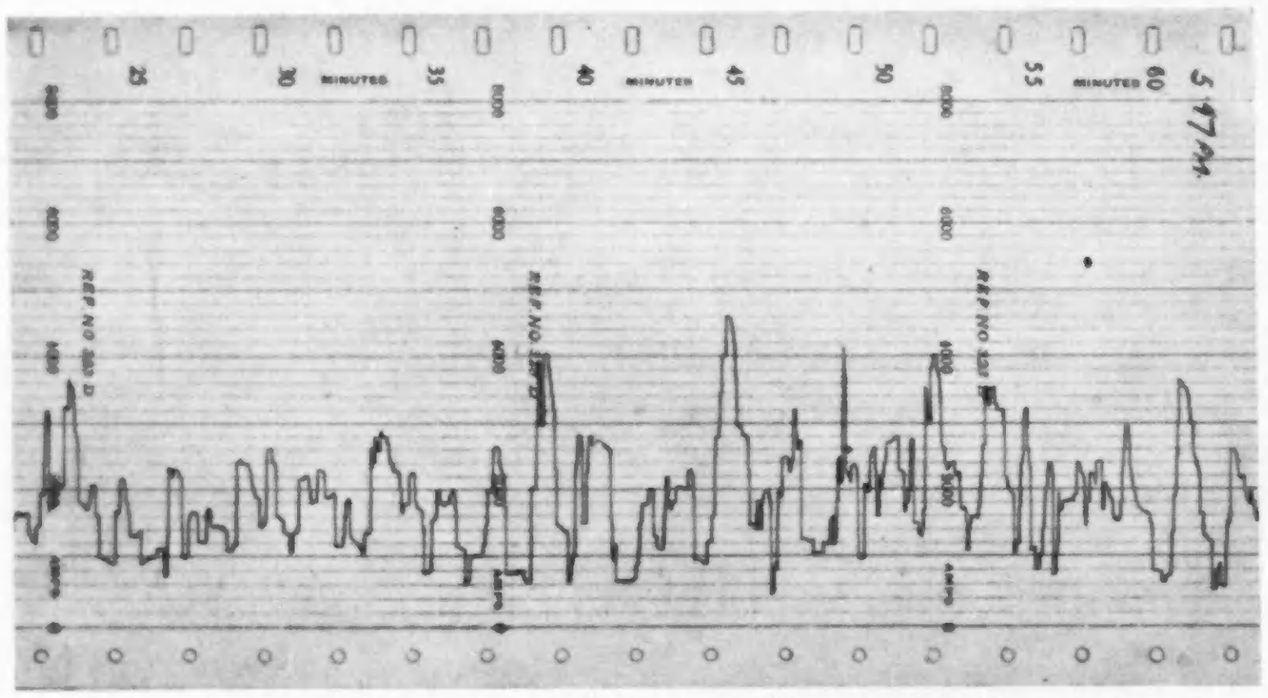


Fig. 16.—Current chart of mercury arc rectifier obtained in service on a traction system.

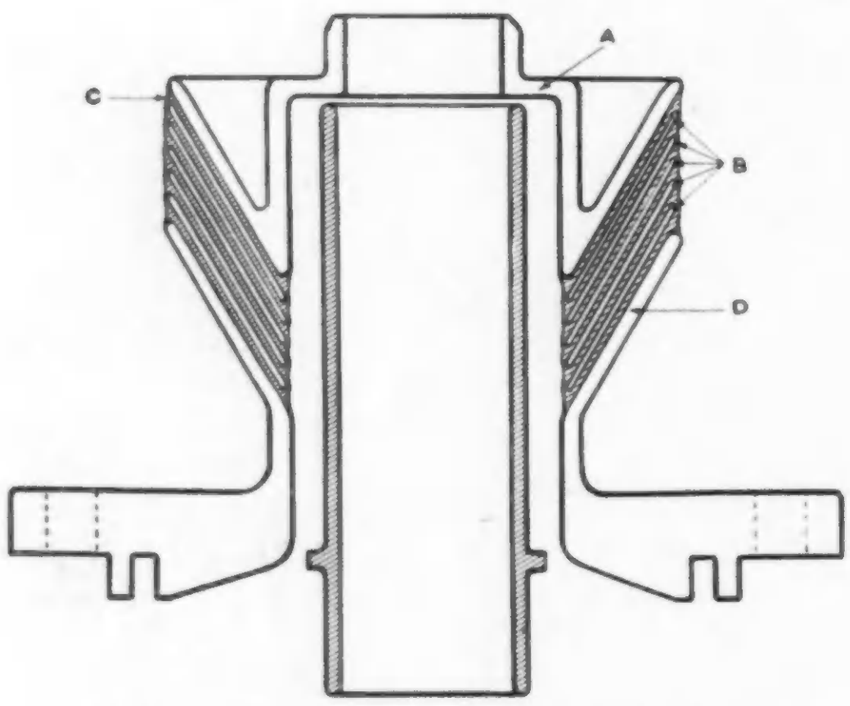


Fig. 17.—Section of vitreous anode seal.

maximum currents as large as 20,000 amps. for a 2,000-amp. rated rectifier.

BACKFIRING.

During the period of development, the prevention of backfiring has claimed by far the most attention as backfiring in the early days was a very serious and frequent occurrence.

A rectifier is said to backfire or arc back when one or more of its anodes act as cathodes. In such cases, not only is the supplying transformer short-circuited, but also the D.C. supply if the rectifier be working in parallel with some other D.C. supply.

Rectifiers seldom rectify perfectly. There is usually a minute inverse current, due to the presence during the burning period of positive ions (positive space charge) in the neighbourhood of anodes. After the close of the burning period, the idle anodes become negatively charged and attract the surrounding positive ions, the flow of which constitutes a current. It is important that the inverse current shall be as small as possible, or loss of valve action may occur. Anything which tends to reduce the effect of these ions is an advantage. The presence of too large an inverse current in the past was probably the most frequent cause of backfires, but it has since been found that the placing of a metallic grid or net in the anode shield close to the anode greatly reduces its occurrence. Such a grid appears to acquire a negative charge during the burning period, and at the close thereof, attracts and neutralises the positive ions.

As the result of the use of these grids, and other features of modern design, backfires are now of rare occurrence, but nevertheless they may happen, either from some part leaking and causing loss of vacuum or specially onerous conditions of load.

When a backfire occurs, especially if running in parallel with other D.C. generators, the amount of energy concerned is very large, and it is important that the rectifier shall be disconnected in the quickest possible time. It is therefore necessary to employ special high speed circuit breakers in the D.C. circuit, and it is also desirable to use high speed A.C. switches, capable of safely rupturing the largest kVA that is likely to be involved when a backfire occurs.

GRID CONTROL.

Grids are sometimes insulated and given other functions by employing suitable arrangements for

separately exciting them, and they may be used for accomplishing a number of remarkable results, which may be summarised as follows :—

(1). Voltage regulation.
(2). Arc suppression after a backfire.
(3). Frequency conversion.
(4). Inversion, *i.e.*, converting from direct current to alternating current.
(5). Replacing commutators in motors, etc.

A grid-controlled mercury arc rectifier is shown in fig. 20.

Fig. 18.—Anode seal and radiator.

It is not proposed to consider these uses of grids in this article, as the subject has recently been fully dealt with by Lewer & Dunham ("Gasfilled Relays," Vol. III, Nos. 2 and 3 of the *G.E.C. Journal*). Although that article deals specifically with gas-filled relays, practically everything contained therein holds good for mercury arc rectifiers with mercury pool cathodes, and with maintained cathode hot spots.

A few of the more important features in the manufacture of steel tank rectifiers will now be considered.

VACUUM.

It is of the utmost importance that a very high vacuum be obtained, and this requires the fulfilment of two conditions :—

(*a*) The rectifier must be vacuum-tight, and
(*b*) The pumping equipment must be amply sufficient.

In tank rectifiers, it is necessary to have a number of joints, some metal to metal and others insulating material to metal, the latter being required in order to insulate the anodes and cathode from the metal tank. Hitherto it has been the custom to employ joints relying on rubber or asbestos, with or without mercury as a sealing medium.

In the G.E.C. rectifiers an entirely new form of seal for the anodes has been developed, and is shown diagrammatically in fig. 17. It consists of a number of thin mild steel cones, B, separately enamelled with a special glass, C. After assembly of the cones and top and bottom members, A and D, the whole is fused up solid in an electrically heated oven. The result is a strong unit having a very high dielectric strength. It is perfectly vacuum-tight and can be bolted down in the simplest possible way to the top plate of the rectifier, and this, together with an improved form of metal to metal joint, enables rubber and mercury seals to be eliminated. A complete anode seal is shown in fig. 18.

Apart from the leakage of air, there is always the possibility of a small amount of occluded air or gas being given off either gradually or in bursts by the steel tank, anodes and the like. It is necessary that

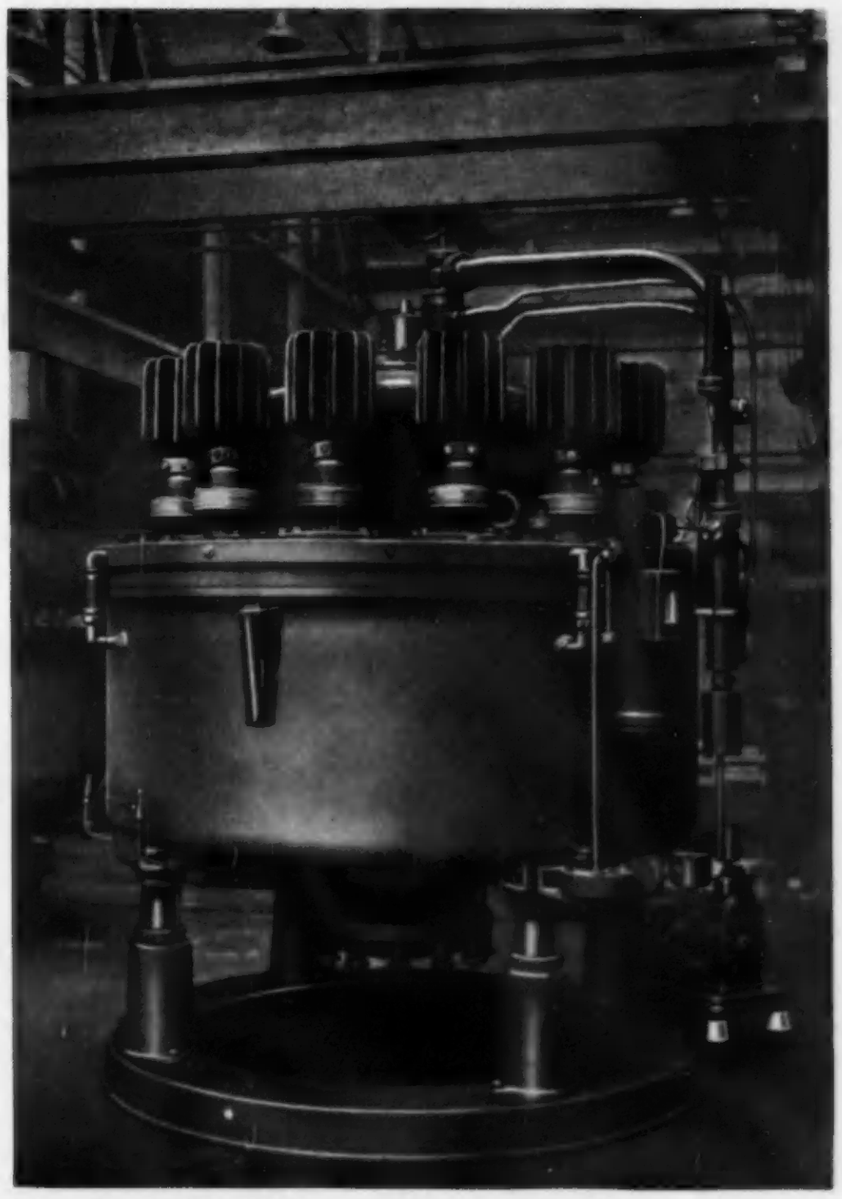


Fig. 19.—1,200 kW mercury arc rectifier assembled at works before testing.

such gas be quickly removed, and for this purpose a pumping equipment must always be in operation.

It is usual to employ two pumps in series ; the first, directly connected to the tank, is a mercury diffusion pump which functions very much on the same principle as a steam ejector. Mercury is boiled by means of a small electric heater, and the vapour passing through one or more jets extracts the air and finally is condensed and returned to the boiler. Although the diffusion pump has a large volume pumping capacity, it cannot operate with

its outlet at atmospheric pressure; a further "backing pump" is therefore employed in the form of a motor driven oil-filled pump which can easily

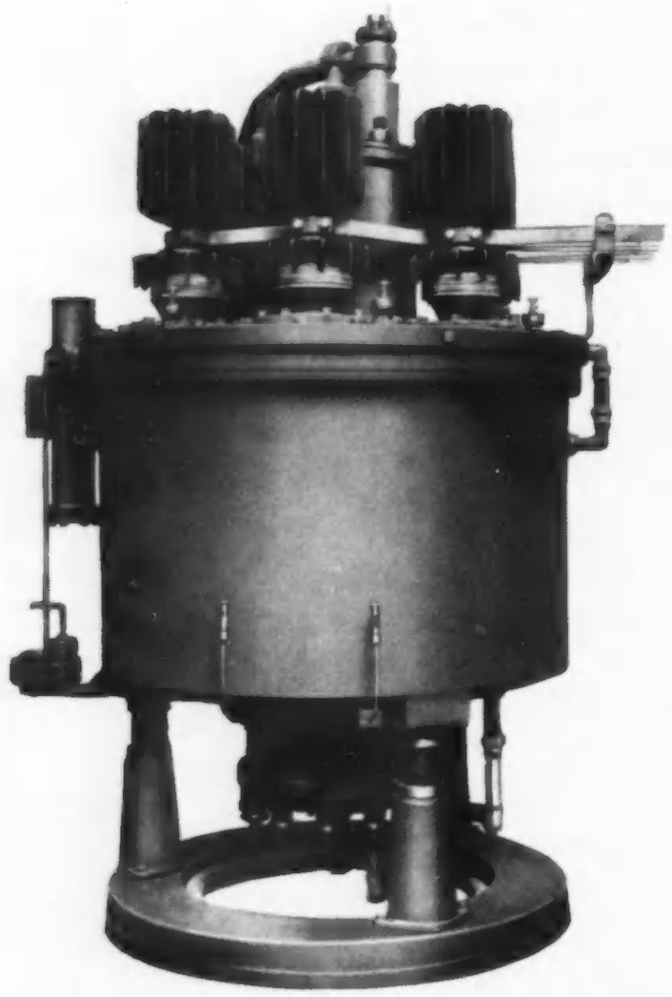


Fig. 20.—G.E.C. grid-controlled mercury arc rectifier.

maintain a vacuum of a few millimetres of mercury at the outlet of the diffusion pump.

By the use of a small chamber between the two pumps, and also a suitable non-return valve close to the rotary pump, it is possible to shut down the latter for a large portion of the working time of the rectifier. In practice the rotary pump only runs for about 12 minutes in 24 hours.

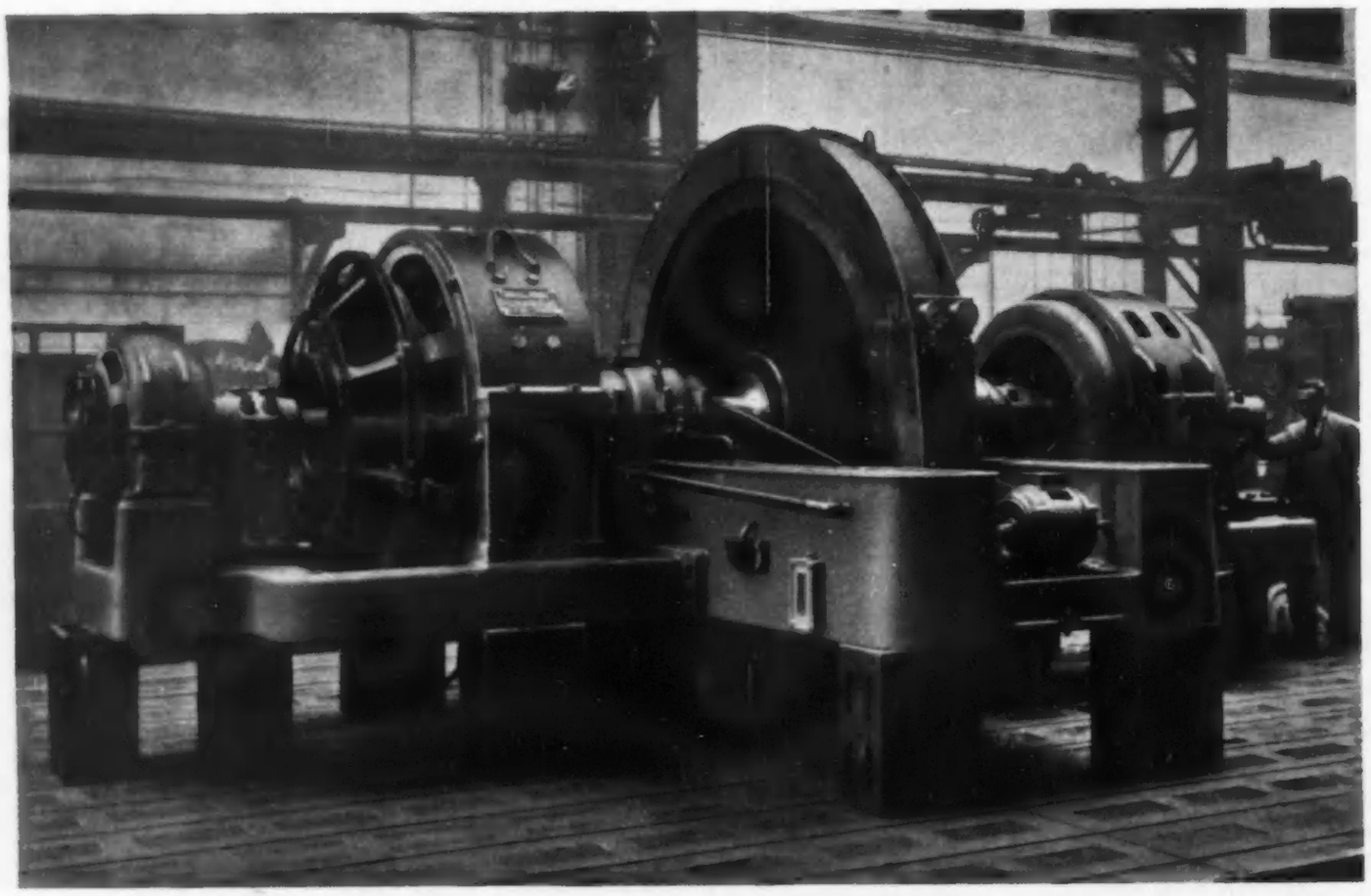
For the purpose of indicating the state of the vacuum, and for operating certain automatic control features, gauges of the Pirani type are employed. This gauge depends for its action on the loss of heat of a fine resistance wire, heated by a current at constant potential. The loss of heat depends upon the density of the gaseous medium surrounding it. Thus, the better the vacuum the lower will be the loss of heat and therefore a higher temperature and resistance of the wire will be obtained. This wire forms one arm of a Wheatstone's Bridge, and any out-of-balance current flows through a milli-ammeter calibrated in microns (1 micron = .001 mm. of mercury).

COOLING.

The losses in a rectifier of course appear as heat, and an adequate water cooling system has to be provided. The simplest method is a supply of running water, but where this is not available, a closed circulating system with forced draught air cooling is satisfactory.

The illustrations of complete rectifiers and rectifier installations shown in this article will give a general impression as to the outputs for which rectifiers have already been constructed.

Electric Equipment for a Yorkshire Colliery.



800 kW Ilgner motor-generator set supplied to a Yorkshire colliery to control a D.C. electric winder capable of raising 250 tons of coal per hour from a depth of 1,710 ft. The set comprises an 850 h.p. slipring induction motor, 3,000 volts, 3 phase, 50 cycles, direct coupled to an 800 kW D.C. generator, 525 volts, 750/650 r.p.m.

The Theory and Specification of Opal Diffusing Glasses.—Part I.

By J. W. RYDE, and B. S. COOPER,

Research Laboratories of The General Electric Co., Ltd., Wembley, England.

This paper was read at the Joint Meeting of the Illuminating Engineering Society and the Society of Glass Technology held at Caxton Hall, London, on the 13th December, 1932. It was subsequenty published in the February issue of the "Illuminating Engineer," from which it is reprinted here.

In Part I of this paper, the Authors' theory of the diffusion of light by turbid media is presented in a simple form which can readily be applied to practical work in connection with opal glasses. Part II will be published in an early issue, and deals with the methods of measurement used in the experimental work and the results obtained, and secondly with certain proposals for the establishment of a figure of merit for opal glasses.

(1) INTRODUCTION.

THERE are two ways in which glasses may be made to diffuse the light falling upon them. In the first place, surface irregularities may be produced by etching or grinding an initially clear sheet of glass, and, secondly, diffusing material can be formed in the body of the glass by introducing certain compounds into the batch mixture. In the latter case the glass is generally spoken of as "pot-opal." Combinations of the two methods are also frequently employed; thus opal glasses containing more or less uniformly disseminated particles may, in addition, be given an etched surface finish. On the other hand, clear glass is often provided with a thin layer of a dense opal glass on one of its surfaces. This form is generally known as "flashed opal," if the coating is very thin, and "cased opal" if the clear and opal layers are of the same order of thickness.

It is now fairly well known that the particles producing the diffusion of the light in opal glasses are quite transparent in themselves. In the same way, cloud or a thick mist may strongly diffuse the light falling on it, although the individual water droplets are clear. The diffusion is, in fact, due to repeated diffraction and reflection of the light by the particles, and this in turn is dependent on there being a difference between the refractive indices of the particles and of the material containing them.

In most opal glasses the particles are generally very much smaller than the droplets which normally occur in clouds or fogs. They are also much more numerous; thus, up to a million million of them may occur in a single cubic centimetre of an opal glass. In the case of the more common "fluoride" opals the particles separate out on cooling, and have been shown[1]* to be composed of sodium and calcium fluorides. Fig. 1 shows a photomicrograph of a pot-opal glass taken with a magnification of 5,000. This was taken with dark ground illumination, and shows the transparent nature of the particles particularly well.

(2) CRITICAL SURVEY OF ATTEMPTS TO FORMULATE A GENERAL THEORY.

Many attempts have been made from time to time by various workers to build up the fundamental theory of the diffusion of light by small particles. It would, however, take far too long to give a complete historical sketch of the work done in this very extensive field. Here we shall give a critical survey dealing chiefly with those parts of the general problem which are more or less directly applicable to opal glasses. The problem naturally divides itself into two parts; the first concerns the way in which light is scattered by a single particle, and the second deals with the resultant effect of a collection of great numbers of the particles when they are distributed at random throughout some medium.

At the end of the last century, the late Lord Rayleigh, in a well-known series of papers, dealt with the way in which light is scattered by a very small particle. He showed, among other things, that the amount of light scattered varies inversely as the fourth power of the wavelength, and thus explained the blue colour of the sky as being due to molecular scattering. He was largely concerned with particles whose size was far smaller than those we meet with in opal glasses, so that this pioneer work cannot be applied to our present problem.

In 1908 Gustav Mie[2] published a classical paper dealing with the scattering of light by spherical

* All references are given in the bibliography at the end of Part I.

particles not restricted in size. The results were extremely complicated, and for every different case very lengthy computations were needed to obtain a numerical result. He showed, however, that as the diameter of the particles was decreased the results became simpler, and finally reduced to Rayleigh's results in the limiting case.

In 1914 Rayleigh,[3] in another paper which is not nearly so well known as his earlier series, gave a simpler theory applicable to any particle diameter,

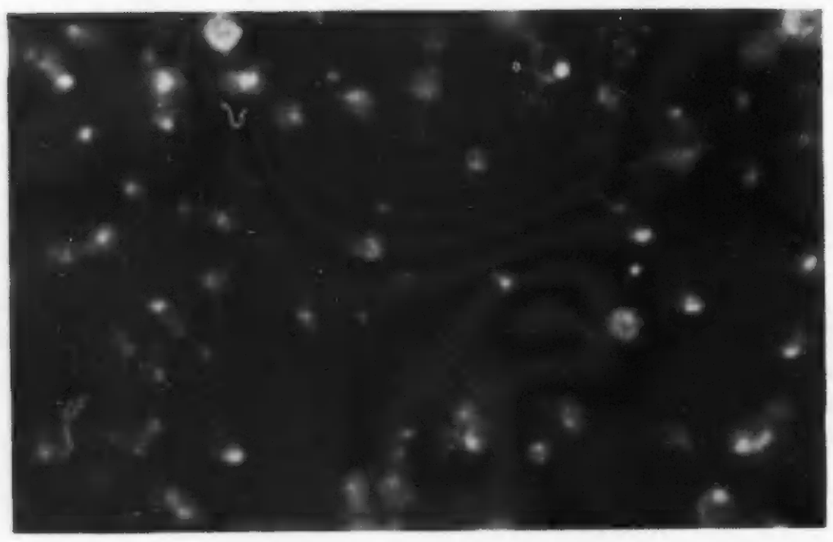


Fig. 1.—Photomicrograph of opal glass with dark ground illumination (Magnification 5,000).

provided that the relative refractive index of the particles and the suspending medium is not far from unity.

Now as regards the resultant effect of a collection of particles, the first step was made in 1905 by Schuster,[4] who first introduced the conception of two diffuse fluxes of light travelling through the medium in opposite directions. Although a certain complication was introduced by the assumption that the particles themselves were emitting light, the case treated was fundamentally almost the simplest possible. The particles were supposed to be so minute that, as was shown by Rayleigh for this case, as much light is scattered in the backward as in the forward direction by each particle. The light incident on the outer layer of particles was also assumed to be completely diffused initially. Finally, any boundary effects due to the medium in which the particles might be suspended were not considered. These assumptions were legitimate for the particular astrophysical case with which he was concerned, but they are by no means allowable in the opal glass problem.

In 1918 Channon, Renwick and Storr[5] developed a theory intended to give the analytical expression for the variation of the transmission and reflection factors of a sheet of opal glass as the thickness is changed. They did not attempt to consider the particles themselves in any way, but they virtually made the same assumptions as Schuster. Their results naturally were effectively the same as his, but they made the mistake of thinking that they would be generally applicable to opal glasses. This is not so, because their method of derivation neglected the boundary reflections and, in particular, the important effect produced by total internal reflection at the glass-air interfaces. Apart from this, their method is sound, but it only refers to the simple case when the incident light is diffuse.

Silberstein,[6] in 1927, was the first to attempt the treatment of the more difficult case for incident parallel or collimated light. He introduced a factor, to be determined by experiment, which would allow for the fact that more light is scattered by a particle in the forward than in the backward direction, except for infinitesimal particles, when the two quantities become equal. His work was, however, entirely vitiated by the fact that he wrongly assumed that the ratio of the amounts scattered by a particle in the forward and backward directions is the same for both the diffuse flux and the residual collimated beam existing inside the glass. This mistake had the result of making his expressions really equivalent to the case for diffuse incident light which had already been dealt with by previous authors. He also made no allowance for boundary effects.

Gurevic,[7] in 1930, gave a treatment of the problem restricted to scattering particles in air and to the case of diffuse incident light. He attempted a method of classification based on his expressions, but this is quite inadequate for the opal glass problem, as he does not consider the amount of unscattered light transmitted (which, as we shall see, determines whether the light-source is obscured by the glass), and again no allowance was made for the reflection effects at the surfaces.

Dreosti,[8] in 1931, gave a theory which covered the cases of both diffuse and collimated incident light, and proceeded to apply it to opal glasses. He however, made the serious mistake of neglecting the effects of surface reflections. He and others appear to have thought that the only surface reflection effect necessary to consider was that due to external reflection. As a matter of fact, the coefficient of reflection of the outer air-glass interface is about 0.04 for parallel and 0.09 for diffuse incident light[10]; these are thus not large. On the other hand, we have found that of the internal diffuse flux arriving at the glass-air surface only about 60 per cent emerges directly; the remainder is totally reflected and has to undergo further diffusion and absorption before reaching the other surface, where the same thing happens again. It will thus be seen that the effect of the total internal reflection is by no means negligible, and that it indeed considerably modifies the predicted values of the proportions of the incident light which ultimately emerge as the transmitted and reflected fractions.

In all the developments of the theory described above, the final expressions did not allow the effects

of given changes in the size or nature of the particles to be calculated. What was always done was to introduce at the start certain constants or coefficients which were unknown functions of the diameter and constitution of the particles. The only exception to this is the special case when the diameter is indefinitely small, but then, as already mentioned, the results are not applicable to the opal glass problem. These constants, or combinations of them, appeared in the final results as symbols whose values had to be determined experimentally for every case.

In 1931 Ryde and Cooper, [9, 10] published a comprehensive theory in which, for the first time, due allowance was made for all the boundary reflection effects, and the necessary constants referred to above were determined in terms of the wavelength of the light, the diameter of the particle and the refractive indices of both particle and medium. In the preliminary work attempts were made to utilize the very general, but extremely complicated, theory of Mie for this purpose. Later it was realized that the Rayleigh theory of 1914 would be quite sufficiently general for all opal glass problems. Even with this simpler basis, however, the development of the expressions for the constants was by no means easy. In order to make the resulting expressions readily applicable in practice, all the functions entailing lengthy computations were worked out numerically and tabulated.

Having found the constants in terms of the fundamental data for the particles, the next step was to determine the transmission and reflection coefficients for a collection of the particles in air. This was done for both diffuse and collimated incident light. Allowance was made in the latter case for the fact that the quantity of light scattered in the forward and the backward directions is different for the collimated and diffuse portions of the flux existing inside the layer. Lastly, the complicated effects produced by the total internal reflection were investigated, and the general theory, including all the boundary reflections, was developed so as to be applicable to particles suspended in any medium.

Since the theory had been developed in terms of the properties of the particles themselves, it was possible to invert the process, and then, as a check, to calculate the diameter and number of particles present from measurements on the transmission and reflection of a sheet of the opal glass containing them. This was done, and good agreement was found between the calculated values and those determined by direct counts and measurement from photomicrographs.[10] Similar tests with suspensions of quite different particles in liquids were also made.[11] These are extremely severe checks of the theory, as will be realized the more if all the varied steps in its development are reviewed. Numerous other tests of the theory will be found in the last papers cited.

Since all previous theories had not included the effects of the internal boundary reflections, it may naturally be asked, why was there not some discrepancy observed when any experimental checks of them were made? The reason is that none of these theories was based on the fundamental data for the particles, so that no searching checks could, in fact, be carried out. The very fact that the values of the constants had to be determined experimentally meant that errors due to neglect of the boundary reflection effects, etc., would be thrown on the constants; these erroneous values were always accepted without question, since there was no really adequate way of testing them. Again, if the faulty values were used to calculate, for example, the transmission of a sheet at some new thickness, the errors would cancel out, provided that the new condition was not too far from the old. When, with bigger changes, discrepancies did appear, the natural explanation would be that the material was not strictly uniform.

The new theory forms a broad basis upon which numerous practical problems concerning opal glassware can be built up. Some of these have already been published. In particular, the theory of the transmission of spherical globes surrounding the light-source has been worked out in detail.[10, 11]

(3) USES OF THE THEORY.

When light is incident on a sheet of glass containing large numbers of scattering particles, some is transmitted, some reflected, and the remainder absorbed. On the other hand, if an opal fitting completely encloses the light-source, a certain fraction of the light is transmitted and the rest is absorbed, partly in the glass and partly in the canopy closing the aperture.

It will, of course, be realized that without any theory to go on, the measurement of these transmission or reflection factors would really tell us very little. Thus we should not know what the values would be if the sheet or globe were made up of a different thickness, nor could the transmission factor or efficiency of a globe be estimated from measurements upon a small sample of the glass. Again, the effect of changing the type of canopy used could not be predicted and, if it should happen that a given sample of glass proved to be unsatisfactory it would not in general be possible to assign the reason.

The object of the present paper is to present the results of the theory in a convenient graphical form and to show how it may then be readily applied to various questions such as these. We shall then go on to show how the intrinsic merit of different glasses, to be used in fittings, can be assessed, and

to illustrate a simple method of specification. Before dealing with these problems in detail we shall devote a little time to the consideration of some rather more general questions.

(4) GENERAL CONSIDERATIONS.

It may be said that calculations such as described in the last section would not be worth while, for the following reasons. First of all, opal glasses are not strictly homogeneous throughout their thickness, nor indeed in different parts of the same globe or sheet. Secondly, glass from the same pot, when blown in different shapes, such as flat sheets, large or small globes, etc., does not always have quite the same properties in each case. This effect is due to the different rates of cooling which entail differences in the particle size and number.

All this is perfectly true, but it is our contention that these changes, provided that their existence is realized, do not detract from the usefulness of the above types of calculation. These considerations are nevertheless important, and, even at the risk of appearing to labour the point unduly, we shall go into them in more detail.

As regards the first point, if, for example, we consider the efficiency of a globe, the variations in different parts of it will average out, unless indeed it is of very poor manufacture. Again, the variations throughout the thickness mainly occur in a thin skin on the surfaces. In practice, therefore, the calculated results will be found to agree quite sufficiently well with those observed. Of course, when accurate tests of the theory are being carried out, the surface skin should be removed. Knowing, however, that variations may occur to a certain extent, one naturally takes the precaution of measuring more than one small sample of any new glass when it is desired to determine its constants. Some idea of the probable accuracy of any prediction based on the mean constants may then obviously be judged from the degree of variation found in the values of the constants obtained from the different samples.

The second point, that glass from the same pot has somewhat different optical properties when made up into different forms, or even similar shapes of different thicknesses, is easily understood. We have seen that with different rates of cooling the particle size and number may differ and so alter the glass constants. Thus, although the manufacturer would say that the different types of article were made from the same glass, it would really be more accurate to consider them as composed of different opal glasses. We have found, however, that the changes in the constants corresponding to alterations in thickness are very small, provided that the thickness exceeds a certain value. Fortunately, this value turns out to be thinner than is employed in opal glassware. It is unlikely, therefore, that this effect will produce any large variations in practice. Hence calculations based on glass from one form of article will generally allow at least a fair estimate to be made of the optical properties of some other form when made from the same glass.

Lastly, it may be said that different consignments of glass may differ somewhat from one another, so that the constants will change. The amount of any such variation depends, of course, on the care exercised by the manufacturer. Until recently there has been no sound method of determining the intrinsic optical qualities of opal glasses, but now that the basic theory has been developed, its use cannot be criticised on the grounds that the product may not be accurately uniform. It is, in fact, one of the objects of the theory to enable any changes in the intrinsic quality of the glasses to be followed, and to indicate the general lines on which an improvement in the optical properties of an opal glass, intended to be used for any particular purpose, may be effected.

The first practical problems to which we shall now give attention are those concerned with the visibility of the light-source.

(5) THE VISIBILITY OF THE LIGHT-SOURCE.

In general, the object of an opal globe is to diffuse the light from the source. In some cases, however, the diffusion is incomplete, and then the source remains faintly visible. In particular, when an electric lamp is used, and the opal does not diffuse the light sufficiently, the filament can be seen through the globe as a sharply defined thin orange or red line. The reason that it appears coloured is that the particles in the glass scatter blue light more than red, and hence a greater proportion of red rays gets through the glass without undergoing diffusion.

In a certain class of glassware, sometimes known as opalescent, this effect is deliberately produced by restricting the scattering power. The particles produced in this glass are generally much smaller than in opal glasses, and, although they may be present in larger number, their diffusing power is considerably reduced owing to their small size. With globes of this type the source appears of a bright orange colour, while the rest of the globe is seen to be of a blue tinge.

On the other hand, in the case of opal glass globes, it is important that the source should not be visible, since otherwise it will detract from the general appearance of the fitting.

Now, even the opalescent types of glass would obscure the light-source if they were made sufficiently thick, while, on the other hand, it can always be seen through opal glasses if they are made thin enough. In other words, what really matters is the amount of diffusing material present between the source and the eye. Since it is impracticable to make

globes either very thick or extremely thin, the main factor in practice is the intrinsic scattering power of the glass.

The first problem which immediately arises is, how is the scattering power to be defined, and the second is, assuming that this be known for a given glass, what will be the wall thickness of a globe which will only just completely obscure the source? A knowledge of this latter thickness is very important. It is, in fact, obvious that if we use a greater thickness than this, the appearance of the globe will not be improved, and yet its absorption will be greater than necessary.

We shall use the symbol q for the total scattering coefficient of a glass and X for its thickness. The ratio β of the brightness of the source, measured through the globe, to its actual brightness is given closely by the following expression, if the superimposed field brightness is left out of account.

$$\beta = (1 - r_o)^2 \, e^{-qX} \qquad (1)$$

Here r_o is the coefficient of surface reflection of the glass, and may for practical purposes be taken as 0.04. It will thus be seen that we can always find the value of q for a given glass by measuring β for a sufficiently thin specimen and then applying equation (1). The details of the measurement will be discussed fully in Part II; here we need only note that, as already mentioned, the proportion of the light scattered, and therefore q, depends upon the wavelength of the light used. For practical purposes we shall assume that q is always measured for an effective wavelength given by the peak of a curve representing the product of the wavelength distribution of the source and the normal luminosity curve for the eye. For gasfilled lamps this effective wavelength may be taken as 5.7×10^{-5} cms.

Now, as regards the second problem: knowing q, how are we to calculate the minimum globe wall thickness X_v that is necessary to obscure completely the source of light within the fitting?

Let c be the candle-power of the light-source, d be the diameter of the globe, and η the fraction of the light from the source which is transmitted by it. Then if $(qX)_v$ is the value of qX when the source is just not perceptible through the globe, we have shown[12] that

$$e^{-(qX)_v} = \phi \frac{\eta}{d^2 \pi} \frac{4c}{b(1 - r_o)^2} \qquad (2)$$

where ϕ is the Fechner fraction and b is the actual surface brightness of the light-source.

From the form of (2) it will be seen that $(qX)_v$ is practically independent of the kind of opal glass employed, because the effect of small changes in η on $(qX)_v$ is slight.

In the case of incandescent filament lamp sources it can be shown that, if the diameter of the globe and its wall thickness X are measured in centimetres, equation (2) can be written in the simple form—

$$(qX)_v = 2.3 \left(\log_{10} \frac{d^2}{W} \right) + p \qquad (3)$$

where W is the wattage of the lamp used. With gas-filled lamps the value of p may be taken as 11.0 for all lamp ratings between about 40 and 1,000 watts.

As a matter of interest, the complete expression for p is given by

$$p = 2.3 \log_{10} \frac{\pi^2 \, b \, (1 - r_o)^2}{\eta \epsilon k \phi} \qquad (4)$$

where ϵ is the efficiency of the lamp in lumens per watt and k is a correction factor to allow for the fact that, although we have measured q for the effective wavelength of the source, it should really refer to the effective wavelength of the emergent unscattered light, which is redder. It should also be noted that, strictly speaking, ϕ depends upon the distance of the eye from the globe; here we have assumed this to be only a few feet, but the change with distance is not large. By experiment we have found that the product $k\phi$ may be taken to be 0.01 if the distance is two feet, and if q is determined for the effective wavelength of 5.7×10^{-5} cms.

Returning to the problem proposed, we now see that, having measured q for a given glass, then for a lamp of given wattage we can immediately determine $(qX)_v$, by means of equation (3), for any desired diameter of globe. The minimum wall thickness X_v which will just obscure the source is then found by dividing $(qX)_v$ by the known value of q. Any greater wall thickness than this will, of course, be inefficient. Naturally, owing to variations in thickness between different fittings and in different parts of the same fitting, a manufacturer must apply a safety factor to the theoretical value of X_v, since this assumes strict uniformity.

The converse problem is also important. Given the lamp rating, the globe diameter and the wall thickness, we can find the value of the scattering coefficient q which must be equalled or exceeded by all glasses which are to obscure the source in the given circumstances. If q is measured for a number of glasses it is thus possible to reject certain of them immediately as being unsuitable for fittings of given dimensions used with specified lamps.

Strictly, the value of $(qX)_v$ derived from the above equation refers to spherical globes. It has been found, however, that the equation is applicable to fittings of quite different shapes (provided they are not very extreme) if the value of d is taken to be that of a sphere having about the same surface area as the fitting in question. It is often convenient to take d to be twice the greatest distance from the approximate centre of the globe to any part of the wall liable to be seen when the fitting is installed.

This will then ensure that the source will not be visible under practical conditions of use.

In order to illustrate how accurately the thickness X_v can be calculated by the above equation, a few comparisons of observed and calculated values are given in Table I. The observed values were obtained as follows: A point on an actual fitting was chosen such that its distance from the filament of the lamp was equal to the radius of a sphere having the same surface area as the fitting. The glass at this point was ground down in stages, and re-polished, until the filament just became visible. To save repolishing the ground surface at frequent intervals, a thin glass cover slip placed over a few drops of xylene (refractive index 1.50) on the ground surface gave the effect of polish whenever it was required to make an observation. When the thickness was reached at which the lamp filament was just distinguishable, the glass was finally repolished. The thin portion was then cut out and its thickness measured. As will be seen from the table, this value was in good agreement with that calculated.

Table I.

	q	$(qX)_v$ by eqn. (3)	X_v calc. (cms.)	X_v obs. (cms.)
Large fitting. Type A	110	12.8	0.116	0.12
Large fitting. Type B	130	12.8	0.098	0.09
Opal lamp bulb ..	230	10.9	0.047	0.05

(6) THE TRANSMISSION AND REFLECTION FACTORS OF SHEETS AND THE TRANSMISSION FACTOR OF COMPLETE GLOBES.

The theoretical work shows that those optical properties of opal glasses which concern us here may all be expressed in terms of the following constants, which are intrinsic to the particular glass:

(1) n_ω, the refractive index of the glass.

(2) q, the total scattering coefficient. This is a function of the number, size and composition of the particles.

(3) NB, a constant composed of the product of N, the number of particles per unit volume, and B, a special scattering coefficient depending on their diameter and the composition. In what follows we shall, in general, treat this product as one constant.

(4) μ, a combined absorption coefficient relating to the glass and the particles.

Now the first constant n_ω does not vary to any great extent for different opal glasses, and may, for our present purpose, be taken to have the value 1.5. The uses of the second constant q have already been fully discussed in the previous section, so that it now only remains to deal with μ and NB.

In the present paper we shall be more concerned with the relationship between these and the photometric properties of the glass than with their intimate connection with the particles themselves. In the cases where the latter is important, the relationship will be explained in more or less general terms. It would take far too long to deal adequately here with this other side of the question, but, if desired, reference can be made to the original papers[9, 10] for the theoretical aspects.

Just as a knowledge of the constant q enables us to calculate the minimum wall thickness necessary to obscure the light-source, so the knowledge of μ and NB allows us to calculate the following photometric factors for any given thickness of glass.

(*a*) The total transmission factor τ' and reflection factor ρ' of an opal sheet, when the incident light is in the form of a parallel or nearly parallel beam.

(*b*) The corresponding total transmission τ and reflection ρ when the incident light is diffuse.

(*c*) The transmission factor σ of an ideal spherical globe of uniform thickness, which completely surrounds the light-source placed at its centre.

From these it is then possible to proceed directly to the solution of practical problems. Thus, to calculate the actual light output ratio of a fitting, we first find σ and then apply corrections to allow for the fact that the aperture is covered with a canopy. But, first of all, we must consider how the constants μ and NB can be determined.

If measurements of the values of a suitable pair of the factors given in (*a*) to (*c*) above are known, these constants can be found. Of the many pairs which might be chosen, we have found τ' and ρ' to be the most convenient. It will be remembered that these refer to the case when the incident light is parallel. We shall defer a description of the apparatus used and the actual method of measurement until Part II. Here it will be assumed that the values of τ' and ρ' have been determined photometrically from a sample of glass of thickness X. The measurements may be made on a plane specimen or on a fairly flat piece cut from a fitting.

The expressions representing the rigid analytical relations between the measured photometric factors and the constants are very complicated. This is so much the case as seriously to hinder their general application, in the original form, to practical work. However, by making certain simplifying assumptions, which are entirely justified so long as we are dealing with opal glasses, it has been found possible to present these relations in the form of simple curves. One set of such curves, connecting τ and ρ with the constants, has already been published,[11] but a new set referring to the more easily measured pair τ' and ρ' will be given here.

The simplifications and approximations employed in the construction of the new curves are as follows:

In the first place, as already mentioned, we shall assume that the refractive index of the glass is 1.5. Secondly, it will be assumed that the absorption coefficient μ is small compared with the scattering coefficient q; this is always the case with opal glasses. Thirdly, it will be supposed that the glass is not so thin, or the scattering power so small, that the proportion of unscattered light emerging is large. This is really no restriction in practice, because no appreciable errors will appear unless so much light emerges without diffusion that the source would be seen very strongly through the glass. Lastly, we shall assume that the ratio τ'/τ is equal to 1.10. The theory indicates that the value of this ratio will always lie between the limits 1.06 and 1.18, and, in practice, it is found generally to be round about 1.10. Various checks we have made show that the likely deviations from this value will not seriously affect the results.

These assumptions greatly simplify the problem and are quite legitimate, except when great accuracy is required. They can be shown to allow the analytical expressions to be represented in a variety of ways, but the following scheme has been found to be the most convenient.

Two families of curves are constructed as shown in figs. 2, 3a and 3b. The first is chosen to represent the relation between σ and τ' for various values of the product NBX, while the second connects σ and NBX for various values of the product μX.

Now, by reason of the following important relation[10].

$$\sigma = \frac{\tau'}{1 - \rho'} \qquad (5)$$

the curves can be immediately used if τ' and ρ' have been measured. On the other hand, they also give directly the value of σ, if NBX and μX are given. The latter case is of frequent use, as we shall see later.

It is important to realize that due allowance for the boundary reflections, both external and internal, has been made in constructing these curves. They therefore apply without any further correction.

It should also be noted that the curves strictly apply only to pot-opal glasses. In general, however, reasonably good results will be obtained in the case of flashed or cased opal glasses, provided that the thickness X is taken to refer to the opal glass portion.

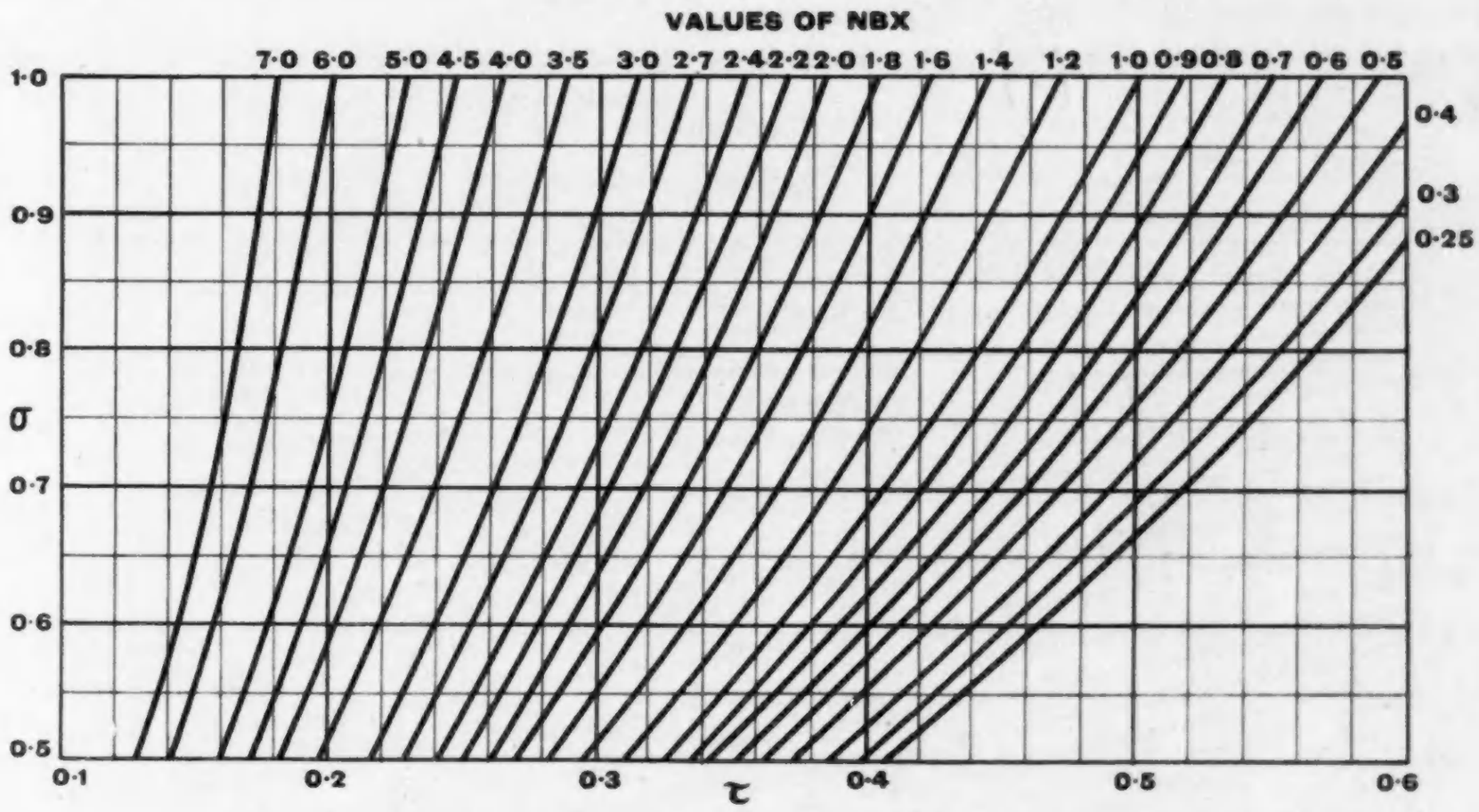


Fig. 2.—Curves of NBX in terms of σ and τ' (Note that $\sigma = \tau'/(1 - \rho')$).

We shall now work out a series of examples to illustrate how the curves can be used to solve a number of different problems.

EXAMPLE 1.

The determination of the constants μ and NB *from measured values of τ' and ρ'.*

Suppose the measured values for a certain specimen of the glass, having a thickness X to be :—

$\tau' = 0.535$ $\rho' = 0.426$ when X = 0.127 cms.

Applying equation (5) we obtain $\sigma = 0.935$, and from the values of σ and τ' we see that from fig. 2 the product NBX = 0.67.

Then knowing the values of σ and NBX, we find from fig. 3a that μX = 0.023.

Since we know X, the values of the two constants follow immediately. Thus—

$\mu = 0.18$

NB = 5.3

It will be seen that a similar procedure can be used if any two of the three quantities τ', ρ' and σ are given, for a known thickness of glass.

Once the constants have been found, the various optical properties of the glass can be determined for any given thickness. How this may readily be done is illustrated in the following examples.

EXAMPLE 2.

Knowing τ' and ρ' for one thickness, to estimate their values corresponding to any other thickness.

Let us use the same data as in the first example. Thus, suppose we are given $\tau' = 0.535$, $\rho' = 0.426$ when $X = 0.127$ cms.

In order to show how well the calculated results agree with observation, values of τ' and ρ' were calculated for a number of thicknesses of a certain glass and curves plotted. These are shown in fig. 4, in which the circles represent experimental values, obtained by grinding down the specimen to different thicknesses and repolishing each time. The constants for the glass used in this test, as determined from figs. 2 and 3a, were $NB = 32.0$ and $\mu = 0.62$. It will be seen that the agreement is satisfactory.*

EXAMPLE 3.

Having measured τ' and ρ' for one thickness, to determine the transmission factor σ of a complete globe made of the same glass, but of some other thickness.

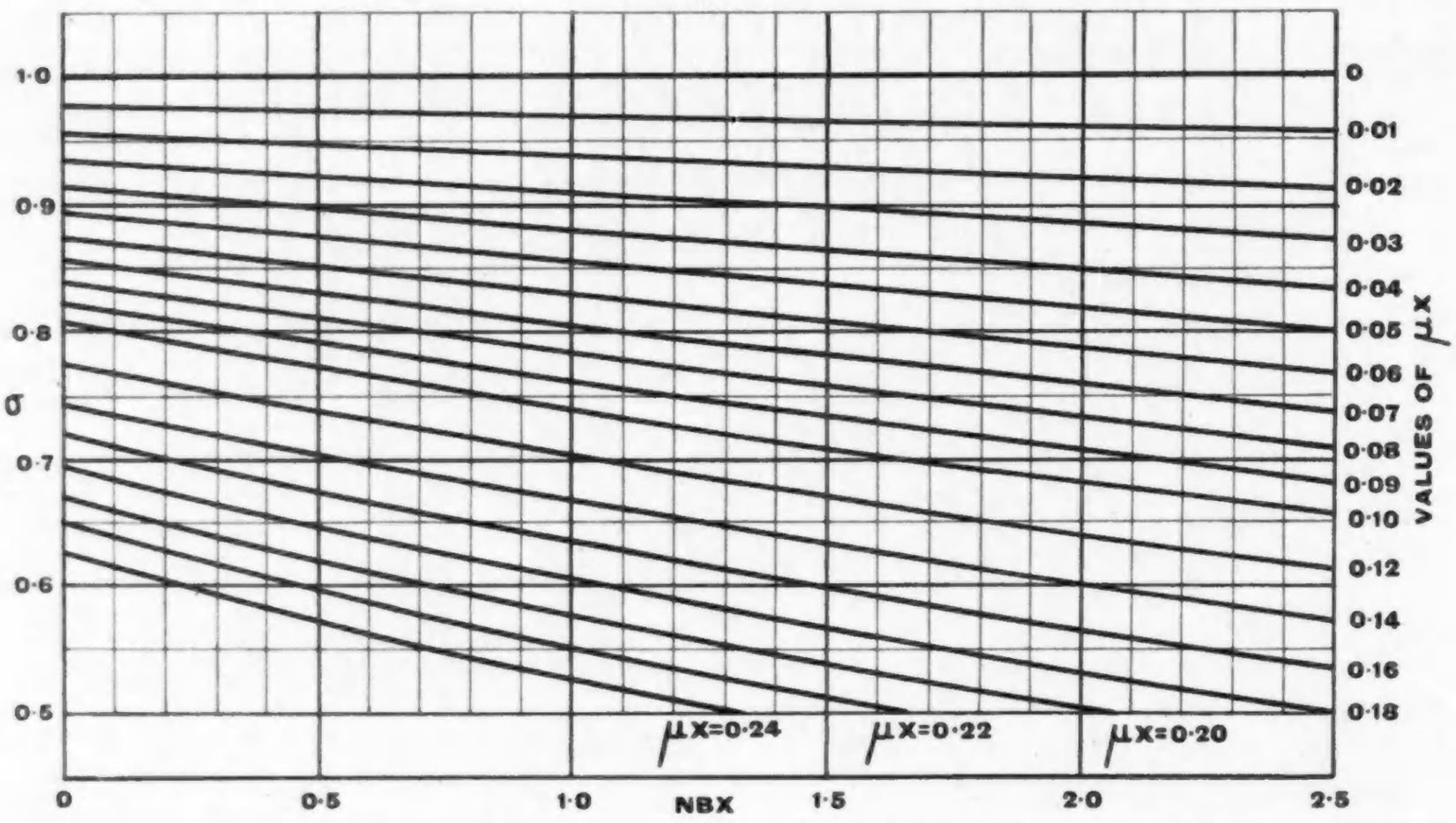


Fig. 3a.—Curves of μX in terms of σ and NBX (Note that $\sigma = \tau'/(1-\rho')$).

By Example 1 we have seen that the glass constants are $NB = 5.3$ and $\mu = 0.18$.

Suppose now that we require the values of τ' and ρ' corresponding to some new thickness X_1, which we will take as 0.09 cms.

Now

$$NBX_1 = 5.3 \times 0.09 = 0.48$$

$$\mu X_1 = 0.18 \times 0.09 = 0.016$$

Then from fig. 3a, using NBX_1 and μX_1, we find $\sigma = 0.955$, and from fig. 2, using NBX_1 and σ, we find $\tau' = 0.578$. But from equation (5)

$$\rho' = 1 - \frac{\tau'}{\sigma}$$

so that knowing τ' and σ, we find $\rho' = 0.395$. Hence the required results are

$$\tau' = 0.578$$

$$\rho' = 0.395$$

Let the values measured for the specimen be

$$\tau' = 0.38 \quad \rho' = 0.54 \text{ when } X = 0.20 \text{ cms.}$$

By using the method of Example 1 we find that the values of the glass constants are

$$NB = 8.2 \text{ and } \mu = 0.25$$

Suppose we wish to find the transmission of a spherical globe having a wall thickness $X_1 = 0.25$ cms. We have

$$NBX_1 = 2.05 \text{ and } \mu X_1 = 0.063$$

From fig. 3a we obtain $\sigma = 0.78$. Thus the light-output ratio of a spherical globe of the given wall thickness, completely surrounding the light-source,

* If the constants had been found by the exact theory, instead of Figs. 2 and 3a, we should have obtained $NB = 35$ and $\mu = 0.60$. Working back from these more exact values by means of the rigid theory, we find that the calculated curves for τ' and ρ' are almost indistinguishable from those given in Fig. 4. As a matter of fact, this glass (having very small particles) is of such a type as to give almost the maximum difference between the approximate and exact values of the constants.

would be 78 per cent, if made of the same glass as the specimen.

In the next section we shall see how this figure is to be corrected so as to allow for the effects of the canopy, etc.

(7) THE LIGHT-OUTPUT RATIO OF FITTINGS.

The light-output ratio of an actual fitting depends not only on the quality of the opal glass globe, but also on many other factors, such as the reflection factor and shape of the canopy. When, therefore, we are interested in the performance of the glassware itself, some standard method of measuring the light-output ratio of the globes is needed. It is desirable that the conditions laid down for this should not differ seriously from the state of affairs obtaining in practice. At the same time, they should be such that the theoretical treatment of the case is not too involved.

A simple method of meeting both requirements is as follows. An uncapped electric lamp is used as the light-source, and it is suspended inside the globe by means of fine wires. The position of the lamp is to be that normally occupied by the light-source when the fitting is in use. In this way, the absorption effects due to the lampholder and support, which may vary in different fittings, are eliminated. To overcome the larger variations produced by different types of canopy, the aperture is closed by a flat plate or card. The side of the card facing the interior of the globe is to have a known reflection factor r, while the other side is to be whitened with the same material as is used to cover the inside surface of the photometric integrator.

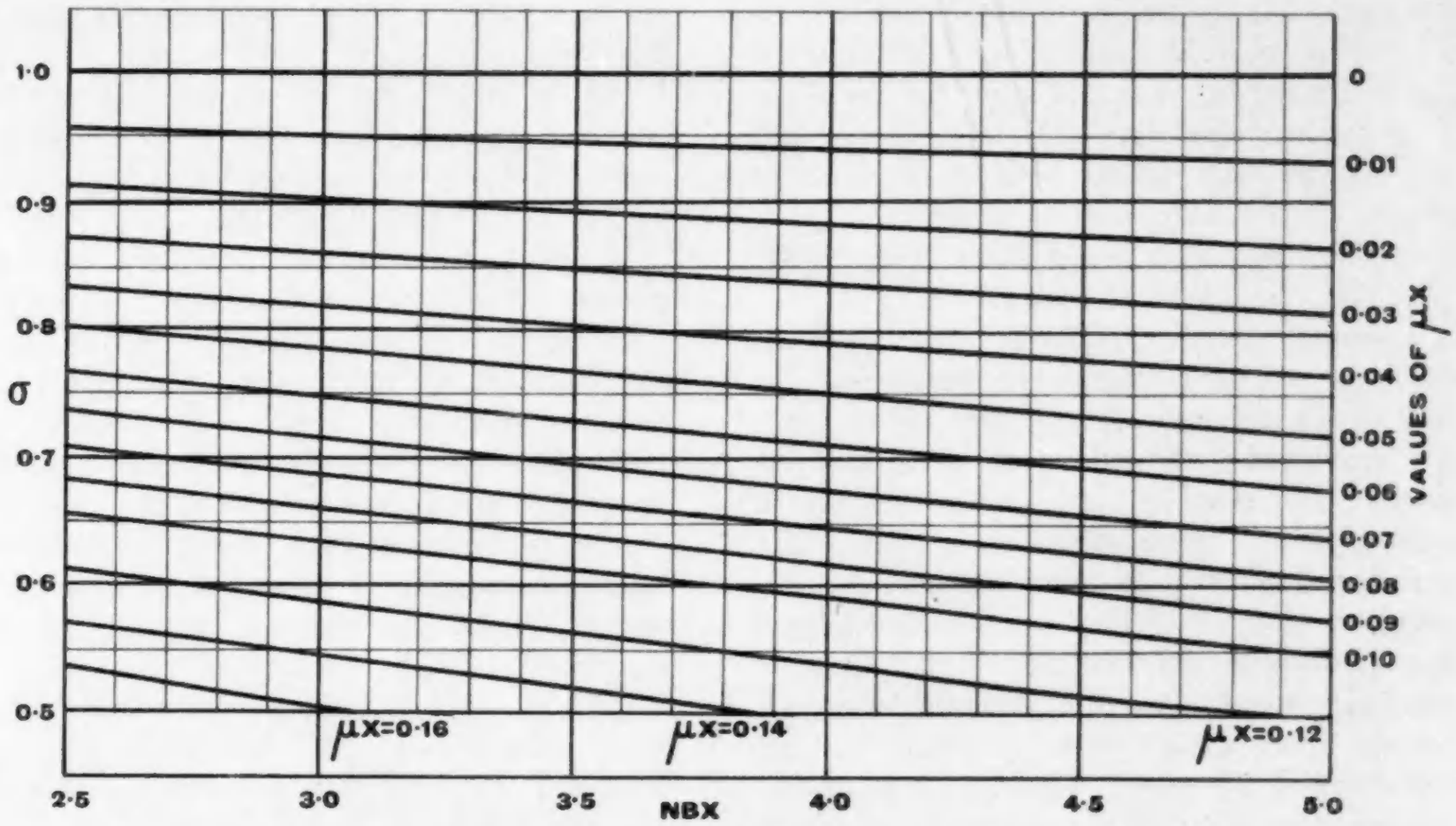


Fig. 3b.—Curves of μX in terms of σ and NBX (Note that $\sigma = \tau'/(1-\rho')$).

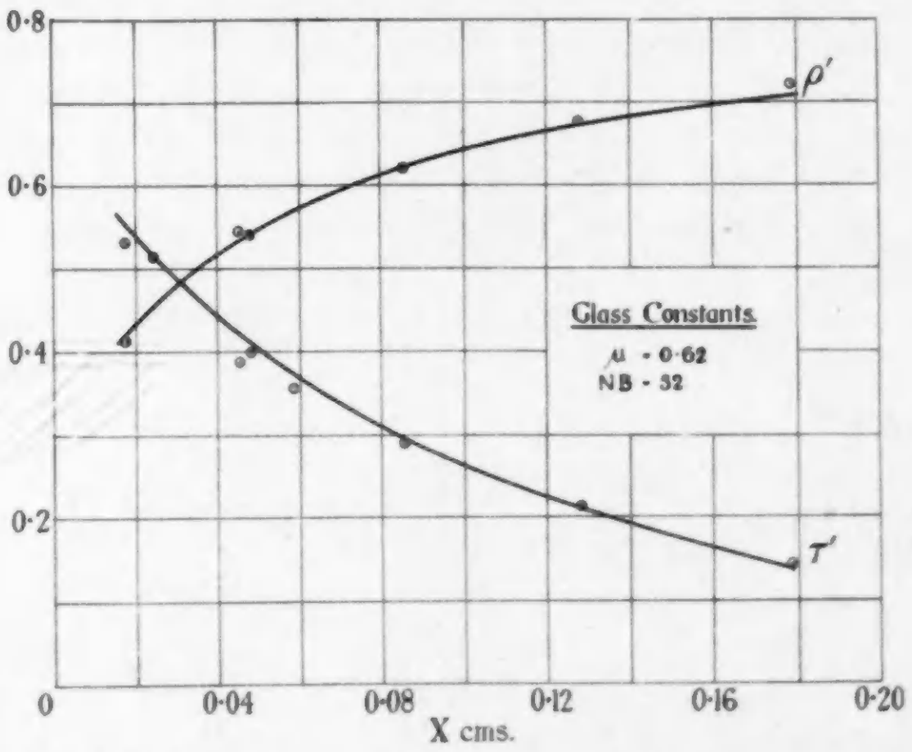


Fig. 4.—Values of ρ' and τ' for various thicknesses of glass.

We shall, in what follows, use the symbol η_o for the light-output ratio of a globe measured under the above standard conditions.

It may be shown theoretically that the ratio of η_o to σ is given closely by

$$\frac{\eta_o}{\sigma} = \frac{1-\rho'}{(r-\rho') + a\,(1-r)} \qquad (6)$$

in which

$$a = \sec^2 \frac{\theta}{4}$$

and θ is the plane angle subtended by the circular aperture at the light-source.*

* It may be noted that, in this expression, an approximate value of the reflection factor ρ' will usually give sufficient accuracy.

The equation shows that the reduction in the light output produced by a given canopy is the more the greater is the value of the reflection factor ρ' for the glass. Also, the reduction increases as the diameter of the aperture increases.

We now see that, by means of this equation, n_o can be calculated in terms of the glass constants μ and NB, since these give σ and ρ' for any given thickness. It is easy to find by experiment the value of r for a card whose effect is equivalent to any given type of canopy. Furthermore, if this is done, an empirical factor can if desired be found, to allow for the effect due to any particular type of lampholder and support. Having once found both of these, it is then possible to estimate from a sample of glass, what the performance of a globe made of it will be under practical conditions of use.

It is, however, not often necessary to go as far as this, and it is usually sufficient to determine the values of r which are equivalent to the various types of canopy employed; the values of η_o referred to any desired r can then be used for the comparison of different globes. These values of η_o may either have been found directly by photometric measurements on given globes or have been calculated from known glass constants. In the latter case the value of η_o corresponding to any wall thickness can be found.

Although, up to the present, we ourselves have always determined the glass constants from photometric measurements on small specimens, it would appear to be possible to determine μ and NB from a sample globe, without having to spoil it by removing a piece. The accuracy may not be so great as with the standard method, but in some cases the advantage of leaving the globe intact would outweigh any possible lack of precision. The method is as follows: The value of η_o is determined as above, using a card of high reflection factor. Then the average value of ρ' can be determined by taking the mean of several observations at different parts of the surface. When taking these measurements, black velvet should be placed inside the globe to exclude light reflected from the far side. A photometer of special design would probably have to be constructed for these measurements. From equation (6) the value of σ then follows. Remembering the expression (5), we see that $\tau' = \sigma(1 - \rho')$, so that we can now proceed to determine the constants, in the manner described in Example 1 of section 6.

As regards the third constant q, which incidentally is only needed when we wish to find the minimum wall thickness to obscure the source, there appears to be no general method of determining it without cutting out a test piece or grinding down a suitable portion. We can, however, determine q, without harming the globe in any way, if it happens to be not too dense to allow a distant lamp filament to be seen through it.

Before going on to show how the theory checks with direct observation, a few general points must be considered. First of all, the theory shows that the effect of non-uniformity of the wall thickness is always to increase the transmission of a globe above the value corresponding to uniform thickness equal to the mean value. The difference is, however, slight, unless the non-uniformity is extreme, such as a variation of 3 or 4 to 1. The distribution of the light will, of course, be different, but the total flux emerging changes only slightly.

Again, it can also be shown that the difference between the transmission factor of a spherical globe and one which does not differ very markedly from this shape is quite small, other things being equal.

Lastly, a word must be said about cases when the glassware has a matt-surface finish. This point was discussed in a previous paper,[11] and we found that the effects of surface finishes, which do not actually contain absorbing matter, should not produce appreciable variations in the transmission factors of globes. This is, however, not the case with opal sheets, so that when determining the constants μ and NB from samples of these special glasses the matt surface should be ground off and the specimen repolished.

We will now show how closely values of η_o calculated from equation (6) agree with those measured. Four different opal-glassware fittings were obtained, and the values of η_o were measured for various values of r, corresponding to different types of canopy. Most of the tests were made with a value of r equal to 0.8, on account of the importance of this case in our proposed method of specification, which will be discussed later. The mean thickness X of each fitting was next determined by the simple method given in Part II. Values of η_o corresponding to these thicknesses were then calculated from the glass constants μ and NB, determined from small samples, in the manner already fully discussed in section (6). In each case the value of θ, for the normal position of the lamp, was 75°.

The results are compared in the last two columns of Table II. The agreement will be seen to be very good.

Table II.

Fitting No.	Glass constants μ	Glass constants NB	Mean thickness X (cms.)	σ calculated from const'nts for a thickness X	r	η_o calculated from σ	η_o measured directly
1	0.40	14.8	0.15	0.78	0.8	0.74	0.76
2	0.20	6.0	0.24	0.85	0.8	0.81	0.80
3	0.24	4.2	0.19	0.87	0.8	0.83	0.83
4	0.18	3.5	0.22	0.89	0.8	0.85	0.85
	0.18	3.5	0.22	0.89	0.0	0.73	0.74

It will be noticed that, in the case of Fitting No. 4, η_o was measured first with a white card of reflection

factor 0.8 over the aperture, and secondly, when r was equal to zero. This latter condition was realized in practice by placing over the aperture a stiff card whose inside surface was covered with black velvet; this has a negligible reflection factor. It will be seen that, although the difference between σ and η_o is, in this case, considerable, the calculated and measured values are in close agreement. The black velvet experiment, in fact, represents the extreme difference between σ and η likely to be experienced with the usual types of canopy, and is therefore an important check on the methods used.

In a further experiment, in which a spherical lamp bulb was used, a piece of glass from another similar bulb was cut so as to fit the aperture where the neck had been removed from the bulb under test. There was thus, in effect, a complete spherical globe of opal glass, and the measured efficiency gave the value of σ directly. The mean thickness of the bulb was 0.093 cms. and the measured value of σ was 0.95. The glass constants were then determined from a sample, and the calculated value of σ for this thickness was found to be 0.96.

The agreement, in the above experiments, between the calculated and measured values is sufficiently good to justify the use of this method of calculation, over the range of values of wall thickness likely to be met with in practice. The method of calculating the value of η_o at any thickness should prove of value in the design and testing of illuminating ware. We shall, in fact, have occasion to use this method later in the section on specification given in Part II.

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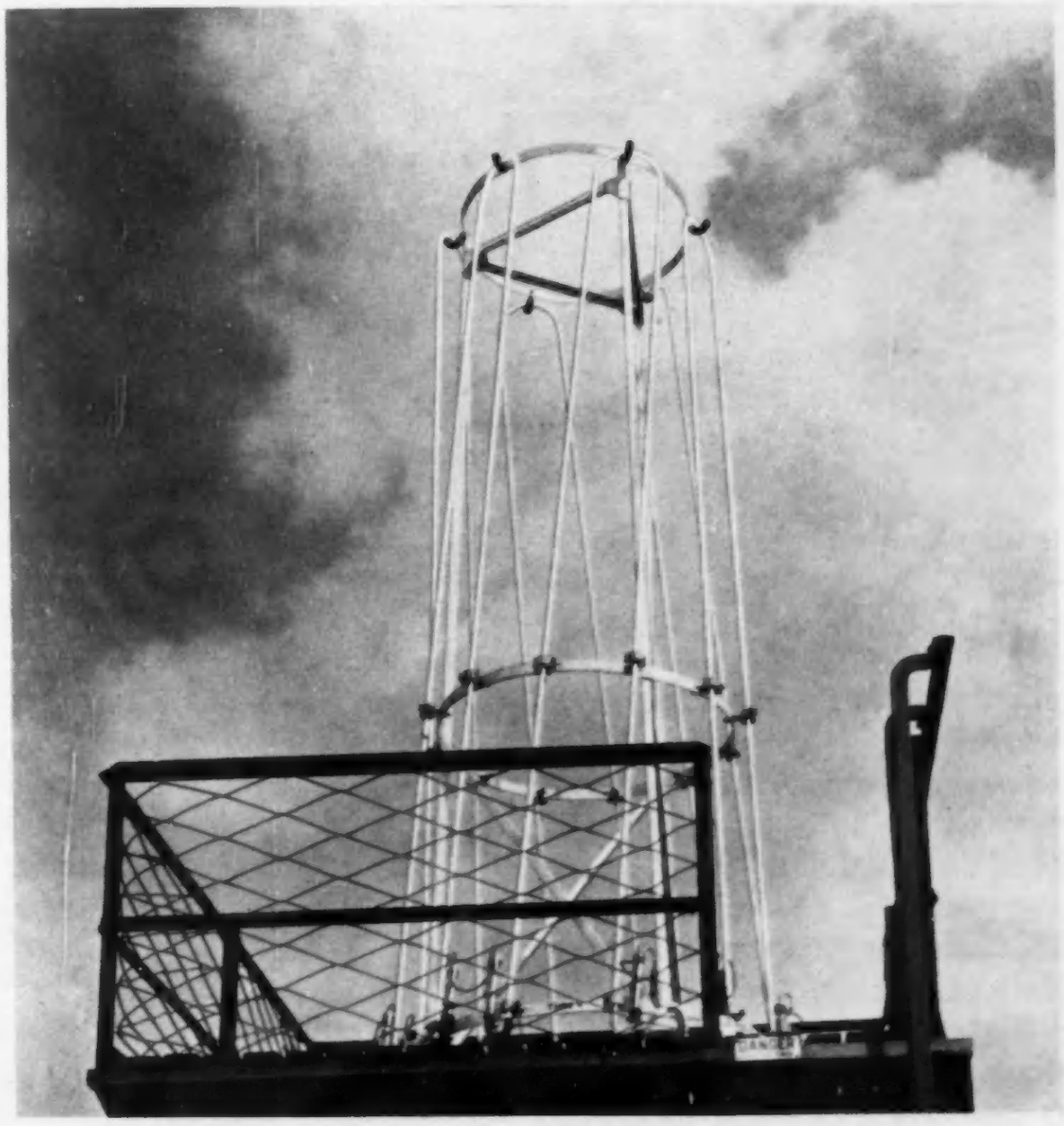
Neon Beacon Light for Aerodromes.



A neon beacon light installed at a British aerodrome.
This form of beacon has been found to be particularly effective during fog and mist.

Electric Propulsion and Equipment of the Q.T.E.V. "Queen of Bermuda."

By C. WALLACE SAUNDERS, A.M.I.Mar.E., A.M.I.C.E., A.M.I.E.E.
Marine Dept. of The General Electric Co. Ltd.
and H. J. COATES
Switchgear Dept., Witton Engineering Works.

BUILT, launched and put into commission during one of the most trying periods in the history of the shipping industry, the quadruple screw, turbo - electric, Furness - Withy Liner, *Queen of Bermuda* demonstrates that British shipbuilding not only maintains, but constantly strives to improve upon, the high standard which characterised those vessels built during a more prosperous era.

embodies such improvements as have been indicated by the service results of the earlier ship. She will replace the ill-fated motor liner, *Bermuda*, which was destroyed by fire about 18 months ago while lying at Belfast. While the new vessel will engage primarily in her owners' service between New York and Bermuda (a service in which the *Monarch of Bermuda* has already obtained considerable popularity) she has also been constructed with a

Fig. 1.—One of the two 7,500 kW turbo-alternators, 3,000 volts, 3 phase, 50 cycles, unity power factor; installed in main engine room.

Work was started on the *Queen of Bermuda* at the beginning of 1932, and the ship left the basin of her builders at Barrow-in-Furness on the 10th February, 1933.

On the 14th of the same month, the ship ran progressive speed trials at Skerlmorlie on the measured mile, over which she reached a maximum speed of 21.07 knots and an average speed of 20.7 knots. Immediately after the speed trials she successfully completed her 42 hours endurance trials.

While the *Queen of Bermuda* is a sister ship to the *Monarch of Bermuda* (described in the *G.E.C. Journal*, Vol. III, No. 1, February, 1932), she

view to her employment for ocean cruising.

As in the case of the *Monarch of Bermuda*, the contract for the building of the hull and for the steam portions of the machinery was obtained by Vickers-Armstrongs Ltd., while the construction of the turbo-electric propulsion machinery and the auxiliary electric equipment of the vessel was awarded to The General Electric Co., Ltd. She was built at Barrow to designs prepared by William Esplen, Son and Swainston Ltd., who have acted in a consultative capacity throughout the construction, while the actual building of both the hull and machinery has been under the constant supervision

of E. W. Harvey, Esq., Chief Superintendent of the owners.

The leading particulars and general characteristics of the vessel are given in the following table.

Length overall	579ft. 6in.
Length on water line over cruiser stern	576ft.
Length (between perpendiculars) ..	550ft.
Breadth, moulded	76ft. 6in.
Breadth, extreme	83ft. 6in.
Depth moulded to A Deck	59ft. 9in.
Depth moulded to B Deck	51ft. 6in.
Depth moulded to C Deck	43ft. 3in.
Load draft	26ft. 3in.
Gross tonnage (approx.)	22,500 tons
Speed (guaranteed)	19¼ knots
Shaft h.p. (approx).	20,000

It will be seen from the frontispiece on page 74 that the hull is of handsome external appearance, with its lofty white superstructure characteristic of the modern passenger liner. The cruiser stern, three black funnels with deep red bands, two well-raked masts, the topsides with a green band at the waterline, a narrow white band above, and the remainder finished in French grey, give the vessel a striking appearance.

Like the *Monarch of Bermuda*, electricity is used on the most extensive scale possible throughout the entire ship, from the actual propulsion and steering of the vessel to the lighting and ventilation of all the public rooms, cabins, etc.; the refrigeration and cooking of food; the handling of cargo; the signalling and indicating devices, and the driving of the laundry machinery, gymnasium equipment, and printing presses, etc. The whole of the electrical equipment required for these purposes was supplied by The General Electric Co., Ltd., and involved the manufacture of turbo-alternators, propulsion motors and control switchgear, auxiliary generating plant, over 270 marine type electric motors for auxiliary machinery totalling approximately 3,000 h.p. in capacity, propulsion cables, all the lighting fittings and over 20,000 electric lamps, switches, electric signs, 600 electric fans, bell pushes, eleven electric lifts for passengers and goods, electric cleaners, a very complete electric cooking equipment, and a number of miscellaneous items too numerous to mention.

MAIN PROPULSION EQUIPMENT.

The *Queen of Bermuda* has four propellers transmitting approximately 20,000 total shaft horse-power continuously. Each propeller is separately driven by a synchronous motor of approximately 5,000 h.p. at a speed of 150 r.p.m. The four motors are supplied with current at 3,000 volts from two 7,500 kW turbo-alternators, running at 3,000 r.p.m. It is possible by the provision of a simple system of switching, which will be described later, to connect each of the propulsion motors to either of the two turbo-alternators, although in normal circumstances the ship functions in a manner similar to a twin screw vessel, the two port propulsion motors operating in unison either ahead or astern from the port alternator, and the two starboard motors operating in unison ahead or astern from the starboard alternator.

Both turbo-alternators, one of which is shown in fig. 1, are situated in the forward engine room, between the two boiler rooms, each set consisting of a high pressure, multi-stage impulse turbine coupled to an alternator.

Turbines.

The turbines are designed to operate with steam at 350 lbs. per sq. inch pressure and 650° F. total

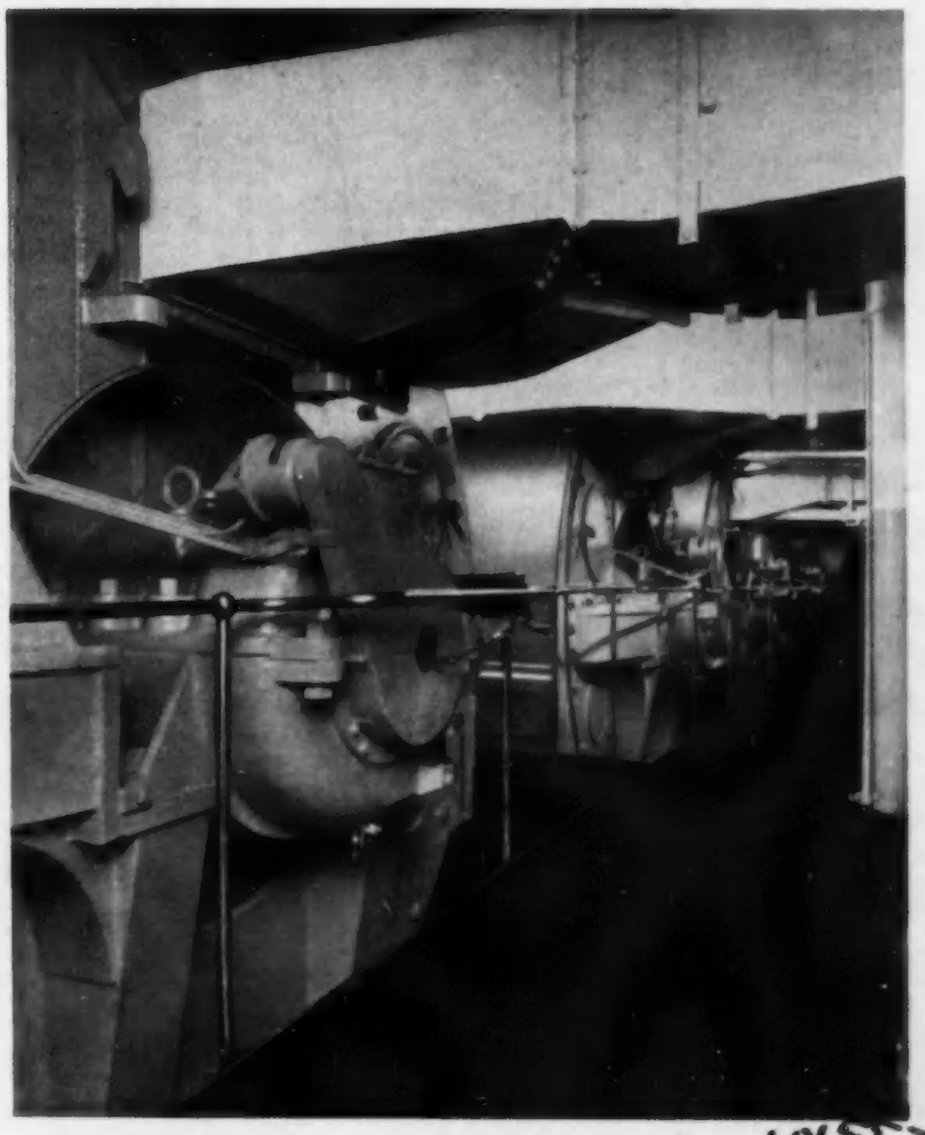


Fig. 2.—General view of the four 5,000 h.p. propulsion motors in after engine room.

temperature, 28 ins. vacuum. They are specially arranged for low head room, having a broad exhaust casing which takes full advantage of the vacuum and provides adequate attachment for the condenser which is bolted on the turbine exhaust flange and supported on springs.

The turbine shaft is rigid and has its first critical speed well above the maximum running speed, while the shaft packings are of Fraser & Chalmers patented labyrinth design. This fitting consists of a forged steel box in the casing of the turbine provided with a number of fine fins projecting towards a similar

set of fins turned on a separate sleeve on the rotor. Both sets of fins have different pitches so that the majority of the fins in the box and sleeve are not situated directly opposite each other. This construction allows a large number of fins to be used with fine clearances without incurring any danger of wear, and in the event of fins making contact, the arrangement is such that they do not touch the shaft, but engage with fins on the wheel hubs or on separate sleeves on the shaft. The heat thus generated by rubbing cannot warp the shaft.

The turbine wheels are pressed on the shaft with the appropriate hydraulic pressure to ensure that they do not work slack at overspeed, while each

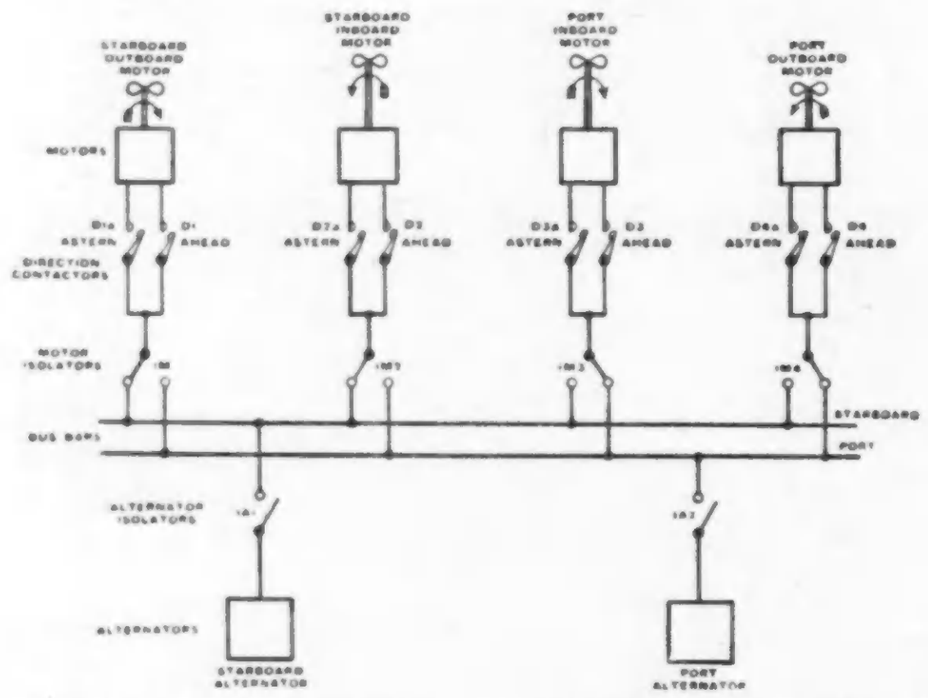


Fig. 3.—Single line diagram of high tension circuits of propulsion equipment.

wheel is mounted on a separate seat and drives on a separate key. The moving blades, which are machined from solid bars of stainless steel, are of heavy section and are individually riveted to the wheel rims. For the first stage of the turbine the nozzles have plates of Hecla A.T.V. cast into the nozzle blocks made from a special mixture of cast iron.

The diaphragms are divided at the horizontal joint, the top halves being held by screws in the top half of the turbine casing so that they can be lifted with the casing clear of the rotor. The guide vanes, which are cast into the diaphragms, are of stainless iron of the correct profile, while the steam nozzles formed by the plates are fescolized. At the exhaust end of the turbine, where the steam becomes wet, the diaphragms are given a special profile opposite the blade tips to trap the moisture which is thrown off by centrifugal action, and to drain it away from the steam passages direct to the condenser.

A Michell thrust bearing is situated at the forward end and locates the turbine rotor. The working faces of the bearing provide ample surface to carry all thrust due to steam pressure and the pitching of the ship, and the design is such that an adequate circulation of oil over the bearing surfaces is assured.

A worm gear, which is fitted in the forward bearing pedestal of the turbine, drives a horizontal spring-loaded speed limit centrifugal governor, while a second worm at the outer side of the thrust bearing drives two oil pumps, one for the lubrication and relay system and the other for the main control device. An emergency governor is also fitted at the extreme end of the shaft to trip the emergency gear at 10 to 12 per cent overspeed and is of the eccentric ring spring loaded type, operated direct from the turbine shaft. For ordinary running, the main control gear determines the speed of the turbines; in emergencies, the centrifugal governor will check the speed of the turbine. The emergency governor is a further safety device which, by tripping the emergency gear, reverses the oil connections to the relays, and assists the springs in closing the stop and throttle valves by applying full oil pressure above the relay pistons and releasing the oil beneath them.

In the main steam chest each valve has its own relay cylinder and pilot valve. The first valve, which is known as the "stop and emergency valve" has a hand gear for securing it in the closed position. This stop valve rises and falls with the main and overload valves, but at a slightly faster rate in order to give the advantage of two stage throttling of the steam, a feature which is particularly valuable at very low speeds, as with the high pressure of the steam used it is essential to have accurate control over very small volumes of steam. The valves and their cages are cut from solid forgings of high tensile steel, while the seats are accurately ported to give the correct load shift characteristics.

In addition to the three governors already mentioned, a further novel safety device is incorporated with the emergency gear to trip the turbine if the vacuum in the condenser fails. The device consists of a spring-loaded diaphragm which is held down by the vacuum so that steam cannot be admitted to the turbine until the condensing plant has been started and a vacuum established. The standard Aspinal oil control gear is connected to the lubricating system to operate the bulkhead self-closing valves on the main steam pipes, and to prevent their being opened until the lubricating oil pressure is established. Provision is made for tripping this gear by hand both in the engine room and from the deck.

The lubricating oil for the turbine and alternator is supplied by the worm-driven gear type pump to which reference has already been made. The pump supplies oil at 60 lbs. per sq. inch pressure for the relays, the pressure being reduced to 15 lbs. per sq. inch through a control valve box for the bearings. Both the bearings and relay systems have relief valves to prevent excessive pressure. At low speeds the full oil pressure cannot be obtained from the main pump, and a motor driven rotary pump with a pressure

relay is automatically brought into operation. In the event of failure of this pump, there is also a steam-driven centrifugal pump with a double pressure relay, which will start automatically if both the main and motor pumps have failed to produce the proper pressure.

Each turbine is controlled by a large handwheel, which is situated on the main control panel in the centre of the engine room. For each position of the control wheel there is a definite turbine speed so that the engineer has full control over the turbine and can raise the speed from the minimum running speed to full speed by the simple operation of this wheel.

A flexible coupling is employed between the turbine and alternator, and is fitted with internal collars to limit the relative movement of the two rotors when the ship is pitching.

Alternators.

As previously mentioned, each of the alternators is rated at 7,500 kW, 3,000 volts, 3 phase, 50 cycles at 3,000 r.p.m., and is provided with a closed circuit cooling system having tubular type sea-water coolers. Both alternators are continuously rated and the maximum temperature rise, shown by the six temperature indicators embedded in the stator and by resistance measurement in the case of the rotor, is substantially within the limits laid down by British Standard Specifications. Mica and micanite insulation are used throughout the construction, and in order to maintain the insulation in good condition and free from condensation during the periods when the alternators are not in use, two 1 kW electric heaters are embodied in the frame of each machine.

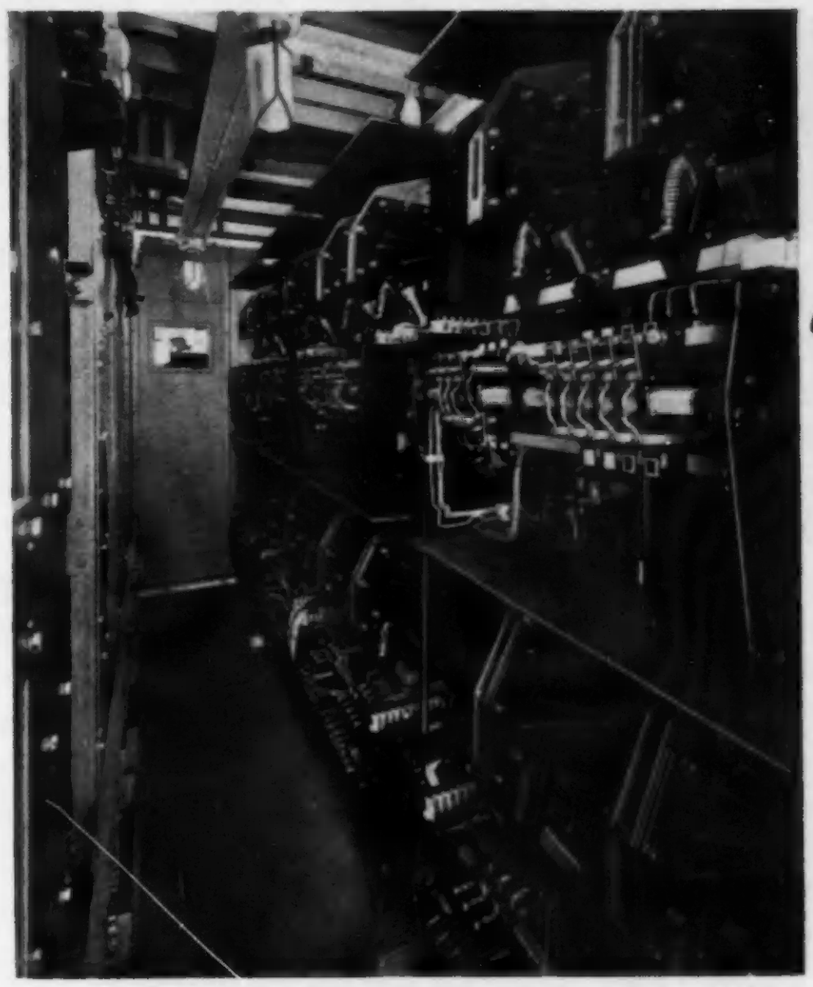


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Fig. 5.—Interior of high tension cubicle, showing direction switches.

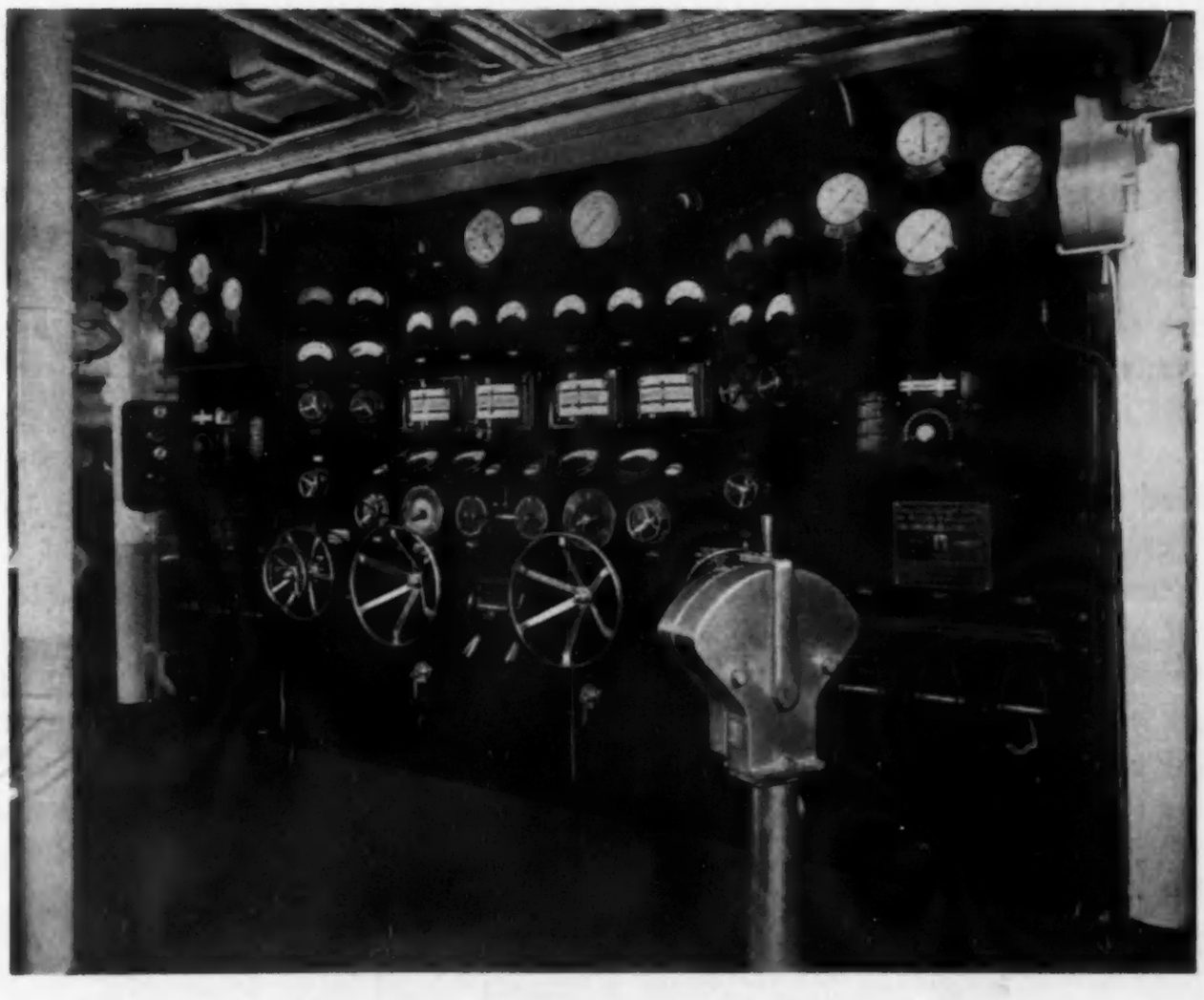

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Fig. 4.—Starting platform of 3,000 volt, 3 phase, 50 cycle propulsion control cubicle.

Excitation is obtained from the 220 volt ship supply generated by the four auxiliary generators which are referred to later. The excitation is in each case applied through the medium of a special negative booster of 28 kW capacity, which provides over excitation for starting. Three booster sets are installed, one acting as a reserve.

Propulsion Cables.

The four propulsion motors, fig. 2, are situated aft in the motor room, the supply from the alternators to each motor being taken through special propulsion type cables.

The design of the Pirelli-General propulsion cables received careful consideration. Two factors had to be borne in mind; firstly, the confined space in which the cables had to be installed and, secondly, the ambient temperature in which they would be called upon to function, bearing in mind that they pass through the boiler room.

These facts being taken into consideration it was finally decided that instead of using one group of

very large conductor single-core cables per motor, a number of three-core cables in parallel should be employed which would be easier to handle in position than the big single-core type. The actual cable installed consists of three tinned copper conductors of .45 sq. in. cross section, insulated with varnished cambric for the full phase to phase voltage of the supply, each core being braided and each phase indicated by colour, the cores wormed circular, lead sheathed and braided overall, and finally impregnated with fireproof compound.

These cables are installed in groups of three, two groups on the starboard side and two on the port side. Great care was required in the installation due to the restricted route of the cables. In passing through watertight bulk-heads, non-ferrous metal packing glands are employed to ensure proper watertight protection between one compartment and the other. The fixing formation is two groups of three placed one in front of the other and supported by means of hardwood cleats fixed to the ship's structure, the ends of the cables themselves being taken to terminal boxes mounted on the motors and to terminal bars in the high tension cubicle.

Propulsion Motors.

Each propulsion motor is of the totally enclosed 3 phase, salient pole synchronous type, provided with heavy damping windings in the pole faces to develop the high torque required during the reversing of the ship. Each motor develops approximately 5,000 h.p. at 150 r.p.m. and is direct coupled to a propeller shaft. In spite of the high power which they develop, the motors are exceptionally light, a feature which is chiefly due to the use of completely fabricated stator and end shields. The shaft of each motor is of massive construction and is supported at each end by bearings mounted on the end shields.

A disc form of lubrication is used, as this has many advantages for a machine operating over a very wide range of speeds, and in particular when running for long periods at very slow speeds. This method of lubrication makes use of a large disc fitted to the outboard end of the shaft, just inside the bearing housing. The disc revolves in the oil, which is brought up to the top of the disc at every revolution. The oil is taken off the disc at the top by means of a metal scraper, and is fed into a trough. It next passes on to the top of the shaft at the centre of the bearing, from which it is distributed along the whole length of the bearing surface, returning by gravity to the oil well.

A separate completely enclosed system of ventilation is installed for each motor and consists of a motor-driven fan and tubular sea-water cooler, together with the necessary trunking.

The insulation throughout is of the highest class in order to withstand possible corrosion by sea air and the moist heat of tropical climates. In particular, the rotor is insulated to withstand the high induced voltages occurring during the reversing of the ship. As in the case of the alternators, electric heaters are inserted to maintain the windings at an even temperature when the ship is in port.

By the ingenious form of construction employed, it is possible to inspect each of the rotors on site by removing the end shields and racking the stator clear of the rotor.

SYSTEM OF CONTROL.

The control scheme will be more clearly appreciated by referring to the diagram, fig. 3, which shows in single line form the switching arrangements of the two alternators and four motors. It will be seen that each alternator is connected to an independent set of busbars from which it may be isolated by means of the switches IA1 and IA2. Each motor is also provided with a two-way isolating switch, enabling it to be connected at will to either alternator. By this means a large number of running combinations are available to deal with various conditions of service, and a high degree of reliability is ensured in case of emergency. It will be seen that each motor is provided with two double pole switches to enable the machines to run ahead or astern.

In starting, the propulsion machines function as induction motors, the sequence of starting being as follows. The steam turbines are run up to about $\frac{1}{8}$th speed without any excitation on the alternator or motor fields. The direction switches are then closed, for either ahead or astern running as desired, and the speed of the alternators is increased to about $\frac{1}{8}$th full speed in order to secure reasonable starting torques on the propeller motors.

At $\frac{1}{8}$th speed, the alternator fields are over excited and the motors begin to revolve, operating for the time being as induction motors, until they reach a maximum speed with the alternators at $\frac{1}{5}$th speed.

The motor fields are then excited and the motors pull into synchronism, continuing to run at $\frac{1}{5}$th speed as synchronous motors. The alternator fields are then reduced to normal excitation, and the speed of the alternator can be varied to any desired value between about $\frac{1}{5}$th speed and full speed. In stopping, the speed of the turbine is reduced to about $\frac{1}{5}$th speed, and all excitation cut off.

Reversal is accomplished by first carrying out the same operations as for stopping, namely, reducing speed to about $\frac{1}{5}$th, opening the excitation circuits, and changing over the direction switches. The starting operations are then repeated.

Various methods of running are available, as follows :—

(1) (Normal working). Two port motors fed by the port alternator, and two starboard motors

fed by the starboard alternator—full speed of vessel obtained.

(2) One port motor fed by the port alternator and one starboard motor fed by the starboard alternator—speed of ship about 70 per cent of full speed.

(3) Four motors fed by either alternator only—speed of ship about 70 per cent of full speed.

(4) Two outboard motors fed by one alternator, and two inboard motors fed by other alternator—full speed of vessel obtained.

All electrical switching operations are carried out at low voltages, thus avoiding the necessity of rupturing heavy currents at the reversing switches. The latter do not operate until all excitation has been cut off, and are thus not called upon to break heavy currents. They are capable, however, of rupturing considerably more than full load current.

With one or more machines out of commission it is necessary to limit the propeller revolutions in order to avoid overloading the plant in commission. For this purpose there are provided two solenoids which act on the turbine governor gear to prevent the speed of the turbine being increased beyond a safe limit. These solenoids are automatically energised to give a limited power condition whenever any of the isolating switches are operated.

If the alternators are each feeding only one motor, similar automatic means are provided to prevent the alternators from supplying more than the normal load of one motor at approximately 70 per cent speed.

In the unlikely event of an operating coil failing in any part of the main control equipment, means

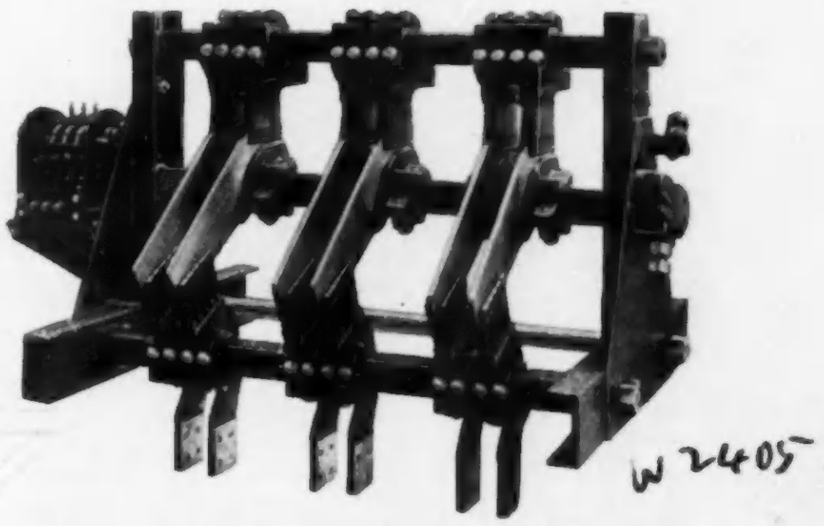

Fig. 6.—Single way alternator isolators.

are provided whereby the entire control sequence may be carried out mechanically without in any way sacrificing the protective features which are obtained in electrical operation. In normal circumstances, however, this alternative equipment is not required for use.

PROPULSION CONTROL EQUIPMENT.

In designing the propulsion control equipment, care has been taken not only to ensure that an alternative means of operation is available, but also to provide ample standby plant and to limit as far as possible the damage which might result in the unlikely event of an electrical breakdown. The main propulsion machines are protected against earths and phase faults by the well-known McColl circulating current system, but using relays designed

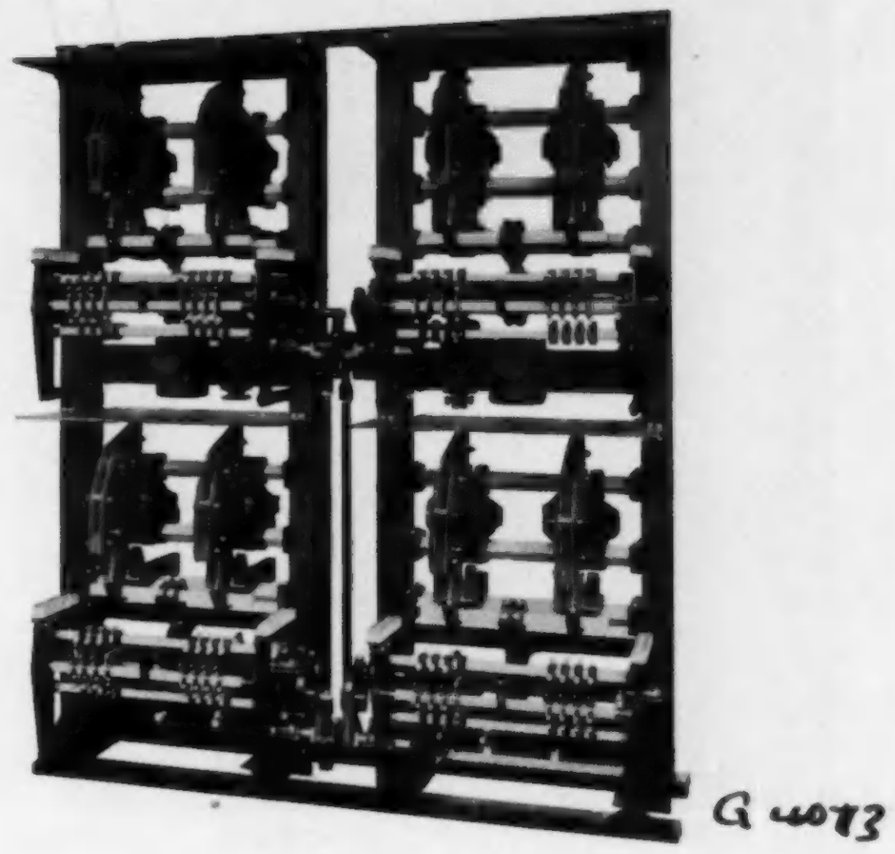

Fig. 7.—Direction switches.

for marine requirements. In place of the usual beam relay, which would be liable to interference from the rolling or pitching of the ship, a special biassed disc type of instrument is employed which has given remarkably good results, its sensitivity and stability being fully equal to that of the more usual type.

As the voltage of the main propulsion system is sufficiently high to be dangerous to life, special precautions have been taken to prevent access being gained to the high tension apparatus while the plant is alive.

The control apparatus is housed in separate steel cubicles, figs. 4 and 5, the first of which forms the actual control panel, fig. 4. These cubicles are installed in the centre of the main engine room, the operator having a full view of the ship's telegraphs. The two larger control wheels in the centre of the control panel are used for the starting sequence, while the two sets of concentric wheels actuate the mechanical emergency mechanism. Above and outside the main control wheels may be seen the two direction control wheels, each of which, in normal operation, controls the direction of rotation of two propellers, while in a corresponding position on the inside of the main control wheels are the two emergency switches which effect the instant removal of all excitation from the corresponding half of the

propulsion equipment. As the main control wheels have a travel of two complete revolutions, a large indicator dial is mounted above each wheel so that the speed setting of the main control wheel may be seen at a glance by the operator.

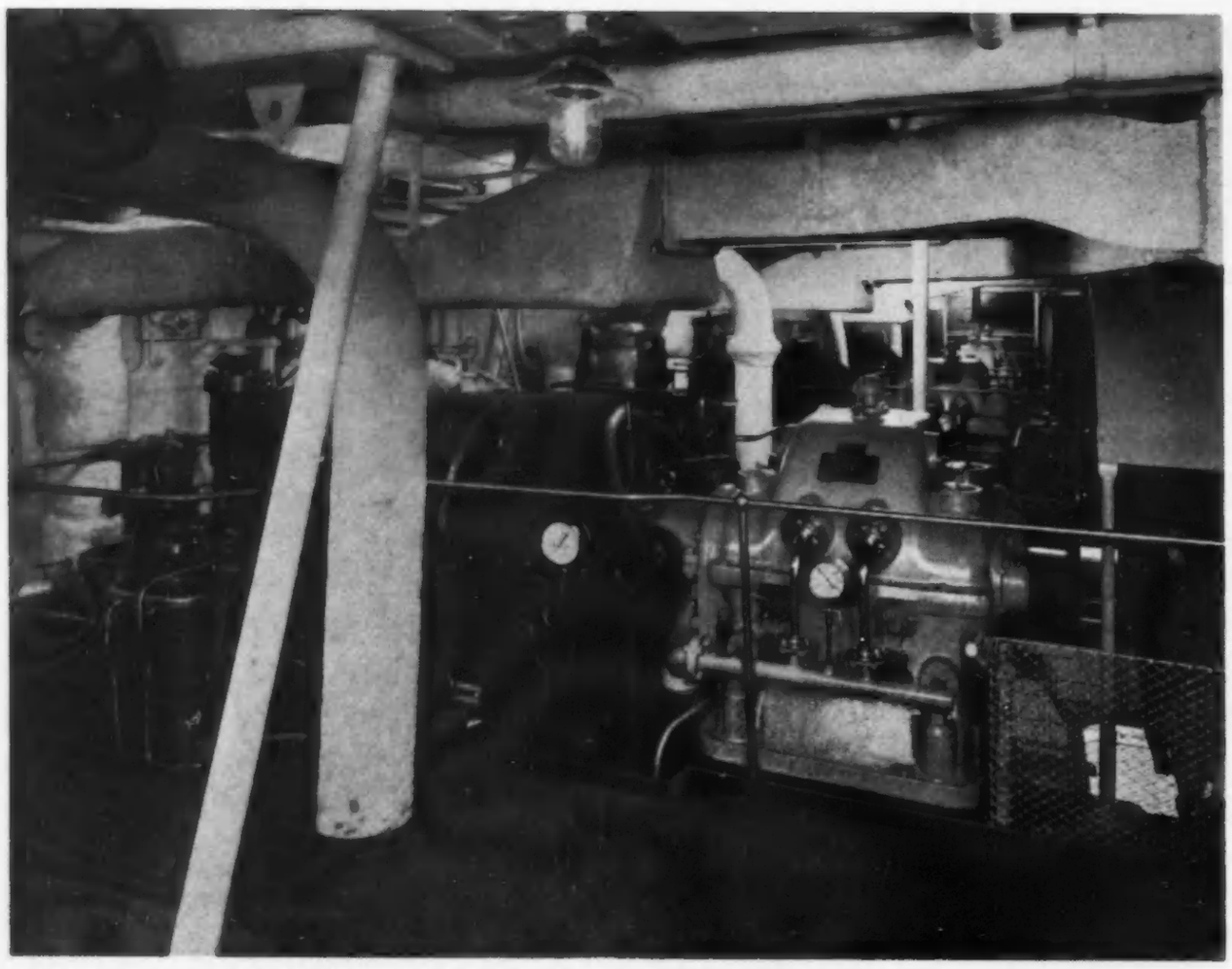

Fig. 8.—One of the four G.E.C.-Fraser & Chalmers 750 kW geared turbines, 6,000/750 r.p.m. driving the auxiliary generators shown in fig. 9.

A propulsion motor may be taken out of service by operating the appropriate motor switch situated just above the indicating dial, while on the sloping desk are the ahead and astern lamps which show the direction of rotation of the main motors. The front of this cubicle also carries four combined motor and alternator speed indicators, the necessary D.C. instruments for the field circuits, wattmeters for each motor, and A.C. ammeters and voltmeters, while alarm bells and lamps for each alternator are provided to inform the engineer in case of an excitation failure.

There are also provided green indicating lamps to show the engineer which of the booster and ventilating fans are running, and temperature indicators for the motors and alternators. The booster field rheostats enable the alternator excitation to be increased if necessary during rough weather. Special stability indicators are provided to indicate the desirability or otherwise of increasing excitation in special circumstances.

The single-way alternator isolators are shown in fig. 6. These isolators, together with the direction switches, are housed in the high tension cubicle.

Reference should be made to the design of the direction switches, which embody the principles of the G.E.C. "line contact" circuit breaker. As may be seen in fig. 7, the unit provides an extremely robust type of latched contactor switch. Shunted blowout coils are used instead of the permanently in series pattern, so that the use of flexible braids is reduced to a minimum.

Behind the outer wing panels of the control cubicle are mounted the alternator, booster, and motor field contactors, controlled electrically from the main control wheels, or alternatively by the smaller wheel of the two concentric wheels used for mechanical operation. The field isolating switches are also mounted inside these wing cubicles and are operated by the three handles in the front of each wing panel.

A booster selector board is mounted at the side of the h.t. cubicle, containing the three starting equipments for port and starboard and spare booster, with suitable change over selector switches by means of which the spare booster may be used for port or starboard side of the vessel instead of the port or starboard booster respectively. This panel also

Fig. 9.—General view in the auxiliary engine room, showing the four G.E.C. 750 kW generators, 220 volts, 750 r.p.m.

carries the temperature alarm lamps and relays for these lamps.

AUXILIARY GENERATING PLANT AND CONTROL GEAR.

The auxiliary engine room houses four 750 kW geared turbo-generators, the turbines running at 6,000 r.p.m., and driving the generators through gearing at 750 r.p.m. The turbines, one of which is shown in fig. 8, are of the high pressure multi-stage type, operating under the same steam conditions as the main turbines previously described.

Each turbine is provided with a constant speed governor, emergency governor and vacuum tripping device. These are similar to those of the main sets except that a spring loaded oil piston is connected to the relay system. When the emergency trip operates, this piston loses its oil pressure and operates a switch which throws out the main circuit breaker, and thus prevents the machine being motored.

Lubricating oil for the turbine, gears and generators, and for the relays is supplied by a rotary gear type pump driven by bevel gears from the governor

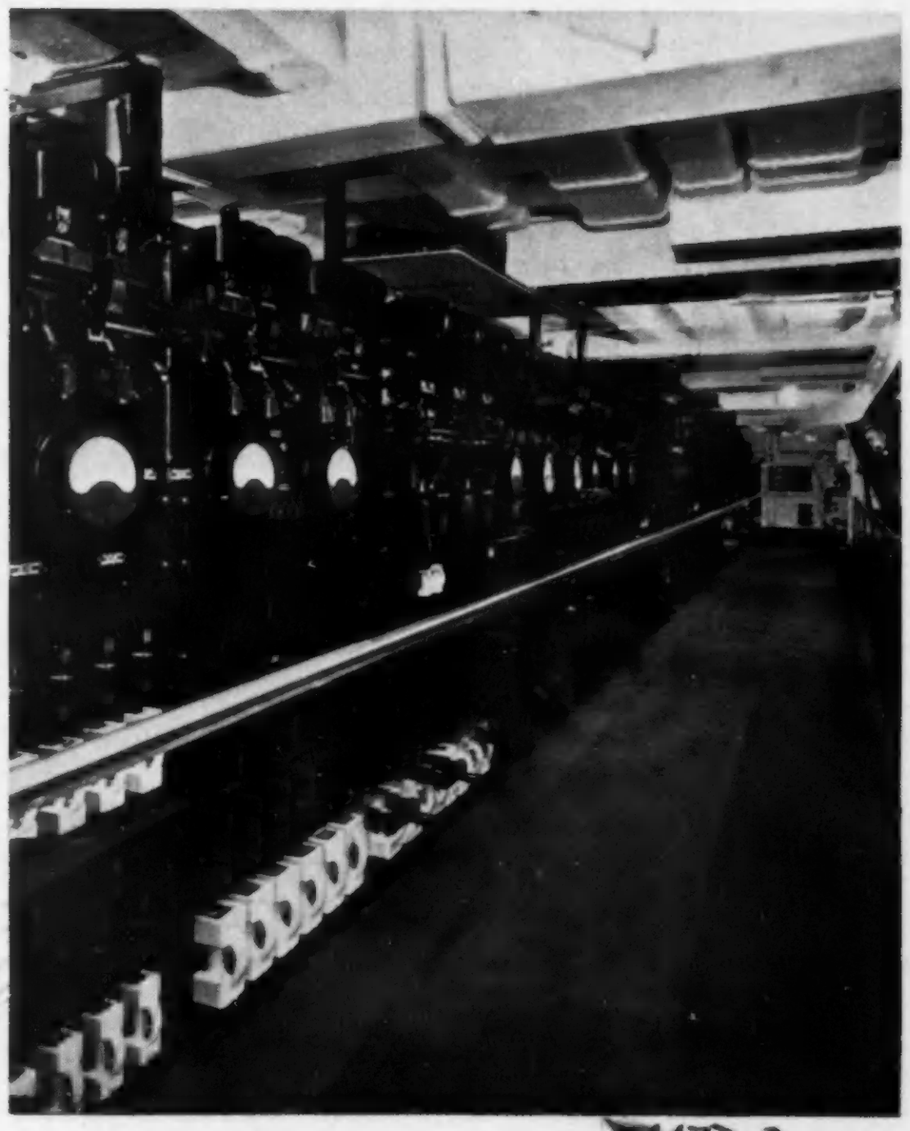

Fig. 10.—Main D.C. switchboard installed in the auxiliary engine room.

spindle. A hand pump is also provided on the oil tank to flood the bearings on starting up.

The emergency valve and its tripping gear are arranged so that on starting up, the spring in the relay cylinder holds the valves shut, and starting gear is provided by means of which the valves can be lifted. When the machine starts, oil pressure is established which lifts the throttle valve further, and at the same time automatically releases the starting gear. As soon as the machine reaches normal running speed the governor operates the pilot and brings the throttle valves into the governing position. Hand gear is provided on the governor casing for

Fig. 11.—"Plural Starter" switchboard in main engine room.

adjusting the running speed for paralleling the machines.

Each of the four generators, fig. 9, is of the open, compound-wound, marine type, generating direct current at 220 volts. All four machines are identical in construction and are provided with special insulation and finish for marine engine room and tropical conditions.

Main Switchboard.

The main switchboard, fig. 10, is 60 feet long and comprises 18 panels controlling the four generators and various feeder circuits for the following services—heating, lighting, galley, deck auxiliaries, propulsion excitation circuits, and various other auxiliary services.

Each of the four generator panels is equipped with a 4,000 amp. triple pole electrically operated line contact circuit breaker, together with the necessary closing contactor and overload and reverse current relay. These circuit breakers are controlled from the central control panel. This panel carries paralleling voltmeters and plugs, generator ammeters, regulators, pilot and earth lamps, and also definite time relays used in conjunction with the overload relays on each generator panel, which control the "non-essential" tripping circuits.

The remaining panels are equipped with meters and 24 line contact circuit breakers ranging from 300 to 1,200 amps., controlling deck auxiliary circuits, propulsion excitation circuits and various

auxiliaries. Below the circuit breakers are mounted the "plural starter" contactor units controlling auxiliary engine room motors. Two of these circuit breakers supply two sets of busbars, to which are connected a number of switches and fuses controlling "non-essential" circuits, while the

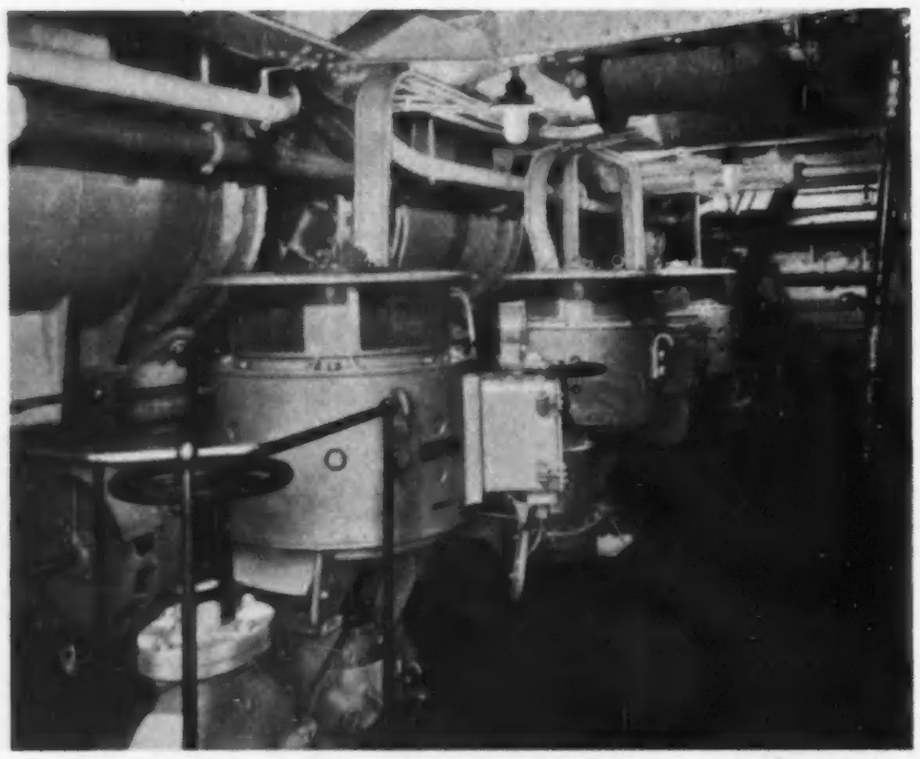

Fig. 12.—Engine room auxiliaries driven by vertical spindle motors.

remainder control various distribution circuits. In the lower part of the board two panels carry fuses and changeover switches for the steering gear motors. Each circuit provided with a meter also has sockets into which may be plugged a recording ammeter.

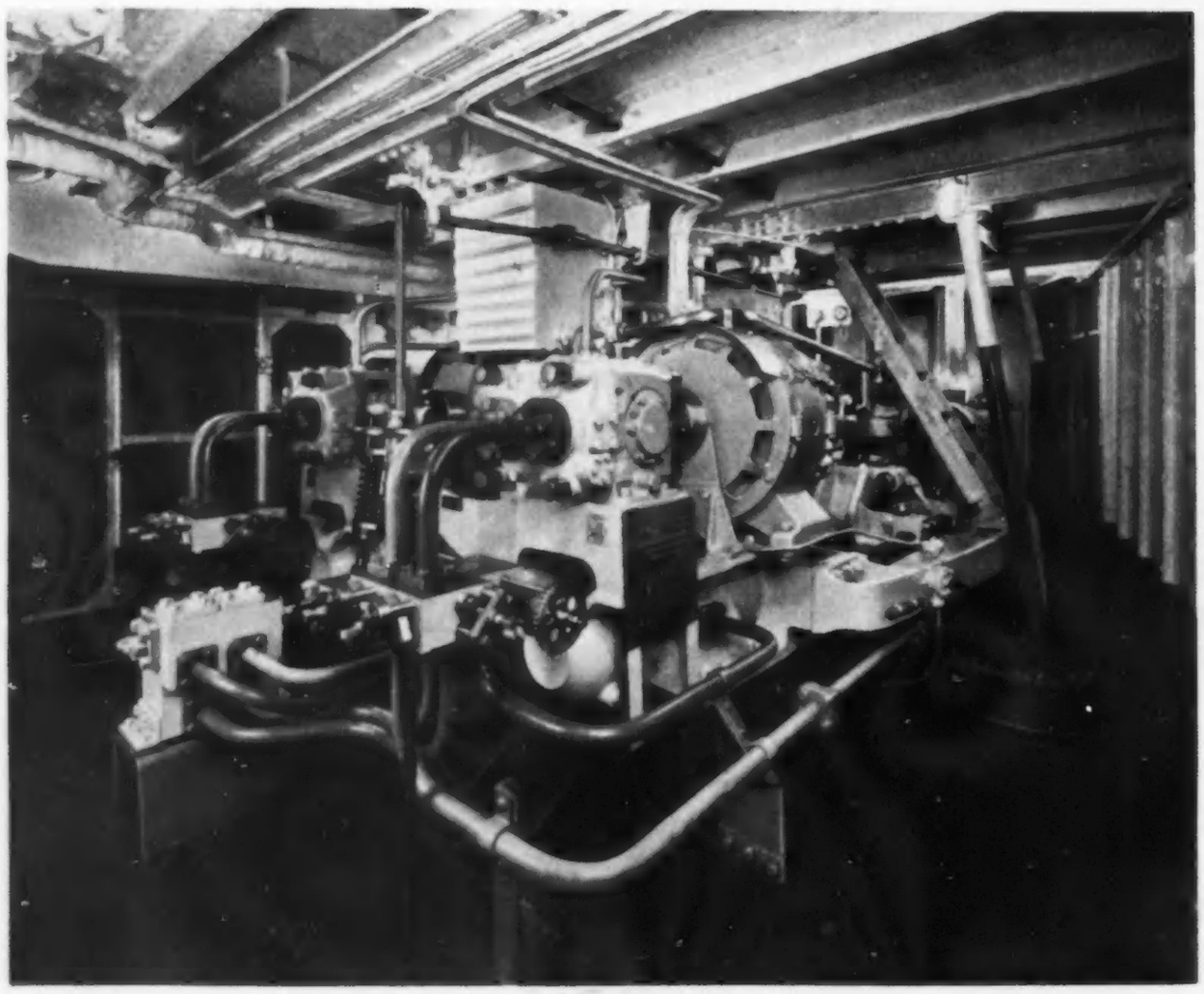

Fig. 13.—42 h.p. main motor and 7½ h.p. emergency motor driving pumping units for hydraulic steering gear.

PLURAL STARTER EQUIPMENT.

A further switchboard, fig. 11, is mounted in the main engine room and carries a second complete "plural starter" equipment to deal with main engine room auxiliaries, distribution switchgear for engine room circuits, and two circuit breakers with change-over switches for D.C. supply to propulsion control. The G.E.C. "plural starter" system is of a particularly interesting nature, the main principle being that one starter only is used for a number of motors, the starter and associated apparatus being located at the main switchboard. In this way a considerable saving in space in the engine room is effected.

The apparatus employed may be divided into three parts:

(1) A control unit for each motor mounted with the motor.

(2) The common starter which is conveniently accommodated on one of the panels of the switchboard on which the starting contactors are mounted.

(3) Two line and one starting contactors for each motor, mounted on switchboard panels, together with the tripping devices or relays which are required.

The control unit consists of start and stop push buttons, isolating links, a shunt regulator; also an ammeter and pilot lamp are provided. It should be noted that the control unit entirely obviates any need for a terminal box on the motor, the control unit being mounted on the motor itself.

The starter is of the motor operated drum type. The drum is mounted on the front of one switchboard panel and the pilot motor on the back. This form of starter is adopted because it is essential to use a type capable of functioning satisfactorily over a wide range of current. The drum is arranged to make a complete revolution at each start, and in order to give a longer starting period for the larger machines, the motor is provided with two independent field windings. One of these is a light series winding so designed that the starting time given by it alone is short and suitable for the smallest machine. The second winding acts in conjunction with the first, and is connected across the starting resistance. When starting a large machine the sustained voltage drop across the resistance energises the winding and strengthens the field, giving a proportionally longer starting period.

The resistance is designed to have a total ohmic value high enough for

the smallest machine, while the later steps are of sufficient section to deal with two or three times the current of the largest machine. By suitable grading it has proved possible to start machines smoothly which vary in horse power in the ratio of 10 : 1. The line and starting contactors are of the usual G.E.C. standard pattern and call for no particular comment.

When the "start" push button is operated two of the contactors close and connect one terminal of the machine to the line while the other is connected to the starter. Simultaneously, the drum starter is set in motion by the pilot motor, and the starting resistance gradually cut out, until finally the third contactor closes, so that the machine is connected to both poles of the supply. As soon as the starting operation is thus completed, the starting contactor is opened and the operation may be repeated for another machine.

During and after starting, the motor is fully protected by the overload relay, which, on tripping, opens both poles of the motor circuit. The system is arranged to work in conjunction with the "non-essential" circuit tripping scheme and certain of the motor panels are provided with shunt tripping coils on their overload relays. Suitable interlocks on the starter render all the "start" buttons inoperative while the starter is actually in use.

Two complete "plural starter" systems, as described above, are installed in the *Queen of Bermuda*, of which the engine room set deals with ten, and the motor room set with 22 motors. Each installation is provided with a standby starter which may be brought into action by a change-over switch. Moreover, each starter may, in emergency, be operated manually.

NON-ESSENTIAL CIRCUIT TRIPPING SCHEME.

The ship's auxiliary supply as a whole is protected by the "non-essential" circuit tripping system. Certain circuit breakers and contactor panels of the "plural starter" installation are provided with a shunt trip connected to one of two busbars. Should the auxiliary generators become overloaded the two busbars are successively energised by timing relays, the first after an interval of 5 seconds from the occurrence of the overload, and the second after a further interval of time. Circuits of secondary importance—*e.g.*, winches, certain ventilating units and part of the illumination—are thereby disconnected when the first busbar is energised. If the overload still persists a further group of circuits is disconnected by the energising of the second busbar, leaving alive only those circuits supplying the most vital services of the ship, such as navigation, engine room, and skeleton lighting throughout the ship, steering gear, propulsion excitation, wireless, etc.

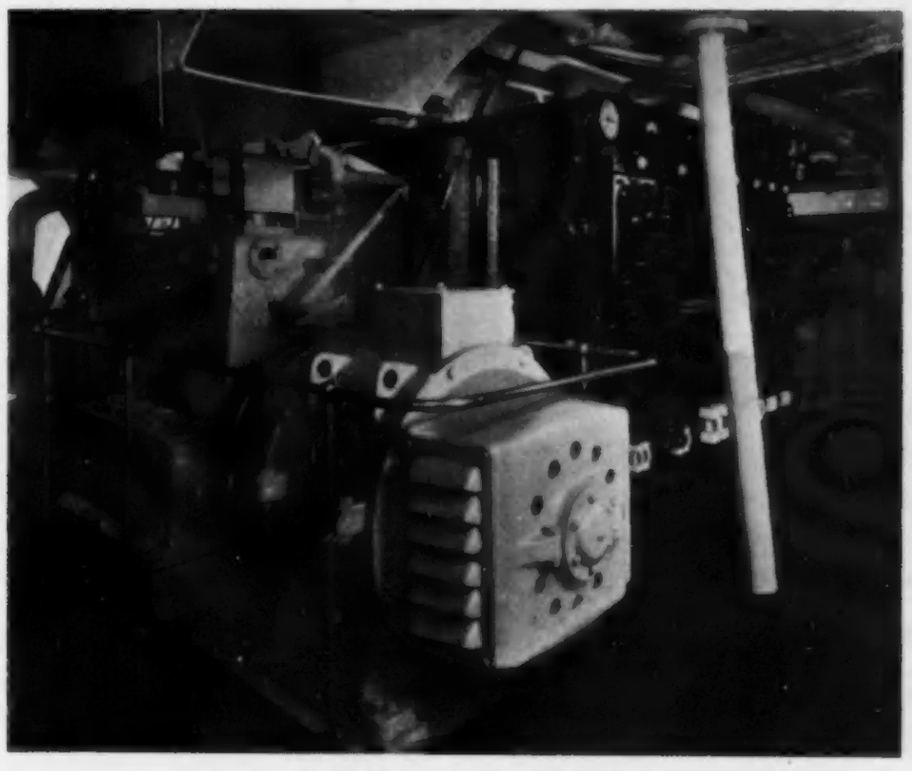

Fig. 14.—70 h.p. motor driving CO_2 compressor for refrigerator.

Under certain conditions this arrangement results in a considerable saving in running costs, as it is possible to run up to the limit of each generator's capacity without endangering the continuity of supply to essential services, with the saving in many instances, of the operating cost of one generator.

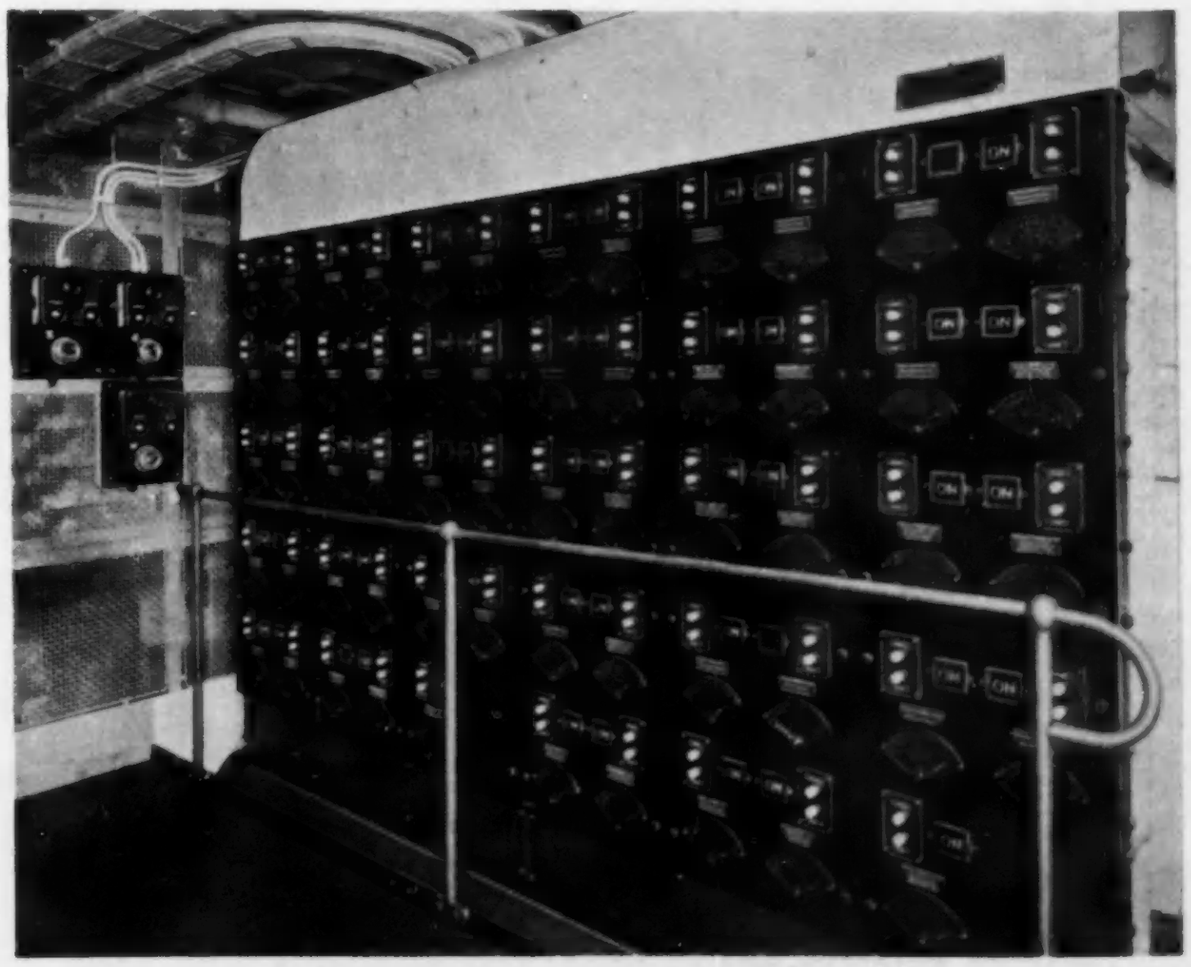

Fig. 15.—The control of 58 motors driving Thermotank ventilating units is centralised on a switchboard. Each unit is started and stopped by a push button.

EMERGENCY PLANT.

For maintaining a supply of power adequate for essential services in cases of emergency, an oil-engine driven D.C. generator of 50 kW capacity is installed on one of the upper decks well above the water line. The output of this generator is controlled by 3 panels of a 6 panel emergency switchboard situated in the same room, the other three panels controlling a "panic" battery and its associated distribution circuits. The change-over of the panic lighting circuits from the emergency busbars to the battery is entirely automatic and takes place on failure of the busbar voltage.

ENGINE ROOM AUXILIARIES.

Mention must be made, before leaving the description of the engine rooms, of the large number of electric motors employed for driving all the auxiliary equipment such as ballast, bilge, sanitary, fresh and salt water pumps, turning gear, forced lubrication, extraction and circulating water pumps, etc. (see fig. 12). All these are driven by marine type drip-proof motors of various sizes and speeds, ranging up to 160 h.p. The motors comply in every respect with the specifications of the appropriate British and American authorities, one particular feature being the impregnation both before and after winding of all coils, a process which renders them fully capable of withstanding the effects of atmospheric conditions prevailing in the tropics.

Most of these units are of the vertical spindle type and are controlled on the "plural starter" system previously described, the "start" and "stop" push buttons being mounted on the frames of the motors.

Fig. 16.—75 h.p. motor driving warping capstan.

STEERING GEAR.

Owing to the confined channels of Bermuda Harbour, the design of the steering gear has received special attention. The electric hydraulic gear supplied by Brown Brothers & Co., Ltd. of Edinburgh, is of the 4-cylinder type with two main and one emergency pumping units, each of the main units consisting of a 42 h.p. motor driving a Williams-Janney variable delivery pump, fig. 13.

The pump controls which are operated from the bridge by Brown's hydraulic Telemotor are so arranged that whichever pump is in action delivers oil under pressure to the hydraulic cylinders, the

Fig. 17.—General view of first class dining saloon, showing lighting scheme.

rams of which are connected to the rudder stock through a crosshead, and cause the rudder to move in exact response to the movements of the steering wheel. Each of the main pumping units is capable of meeting all ordinary steering requirements and, normally, one unit is in reserve, arrangements being provided for changing instantaneously from one unit to the other, or for running both together in close waters.

The emergency pumping unit, driven by a separate $7\frac{1}{2}$ h.p. motor, is operated from the ship's panic battery and is arranged to come into action automatically if the supply to the main motors should fail, and to be interrupted automatically as soon as the main supply is restored.

The main motors are controlled by contactors operated by "start" and "stop" push buttons provided in the wheelhouse.

REFRIGERATION EQUIPMENT.

In view of the large amount of perishable foodstuffs which have to be carried by a vessel of the size of the *Queen of Bermuda*, extensive refrigerating plant is required. In consequence, two plants have been installed in connection with the insulated holds, by J. & E. Hall, Ltd., of Dartford,

one of which is situated forward and the other aft. In all, 23 motors are employed for driving the various sections of these equipments, the largest being a 70 h.p. machine driving a CO_2 compressor, fig. 14. Each of the larger motors is operated by stop and start push buttons, the smaller motors being operated by direct starting switches. Each equipment is provided with a slate panel switchboard for controlling the incoming supply and the motor circuits.

Fig. 18.—First-class lounge, illuminated by indirect cornice lighting and glazed and floodlighted laylight ceiling.

1018-38

VENTILATION.

The unusually extensive scheme of ventilation adopted on the *Queen of Bermuda* represents a very successful attempt to counteract the effects of the very humid atmospheres encountered, particularly in the Gulf Stream which is crossed on the New York—Bermuda route. The frequency with which the air is changed inside the ship exceeds by a very large margin the requirements of British and foreign authorities.

While the various cargo holds "'tween decks" and some of the less important store rooms are ventilated naturally by the usual cowl ventilators, the whole of the accommodation is ventilated by the Thermotank system employing over 100 ventilating units, each of which incorporates a fan driven by a small silent marine motor. The control of 58 of these units is centralised on a starting panel, fig. 15, from which each unit can be started or stopped by a push button. In addition to this, all cabins, saloons, etc., are provided with Magnet ceiling fans or Gyro 2-speed fans, of which a total of approximately 600 has been supplied.

For the ventilation of the engine room, which was carried out by Thermotank, Ltd., 9 motors totalling 120 horse-power are employed.

DECK MACHINERY.

The deck machinery supplied by Clarke, Chapman & Co., Ltd., comprises a powerful naval type of windlass, four warping capstans, fig. 16, and four winches. The windlass is driven by a 150 h.p. motor, while the capstans and winches are driven by four 75 h.p. and four 25 h.p. motors respectively. The windlass is capable of lifting 28½ tons at 38ft. per minute, while the winches can be coupled together in pairs, if required, and can thus deal with maximum loads of 15 tons at 30ft. per minute. An interesting feature of the winches is that portable controllers are supplied which can be strapped to the shoulders of the operator; he is thus free to move about and at the same time to control the winches while watching the handling of the cargo.

Fourteen Fleming patent life-boats are provided, twelve accommodating 99 persons each, and two accommodating 55 persons each. The life-boats are carried in Welin-MacLachlan gravity lowering davits. For raising the life-boats, eight 15 h.p. motors are installed, controlled by water-tight drum controllers. The life-boats can be launched by gravity from the stowed position on deck, with or against any list up to 30 degrees by the one operation—"lowering." All the boats are fitted with Fleming hand propelling gear, shock absorbing lifting hooks and folding sea-anchors.

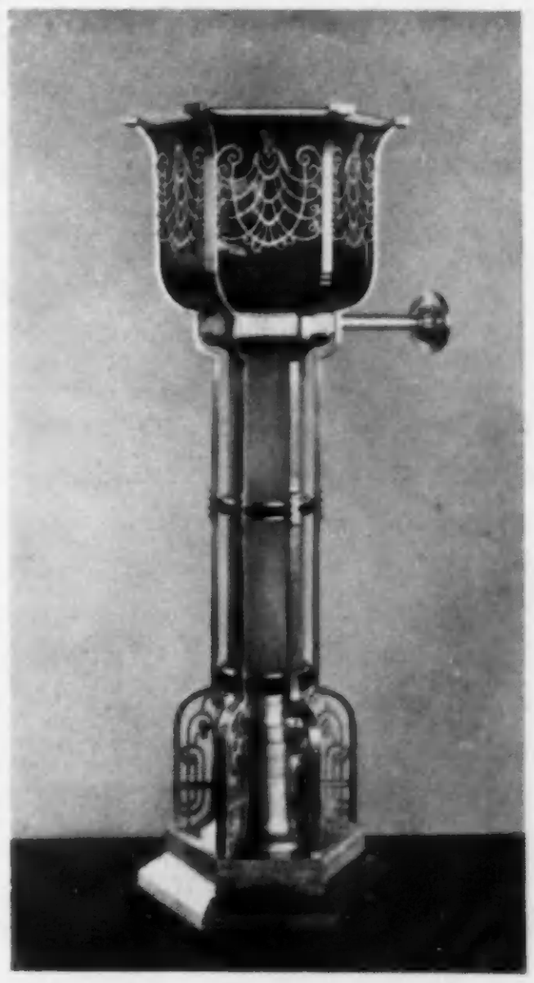

Fig. 19.—One of the four lighting standards, situated in the first-class lounge.

ILLUMINATION.

The lighting of the ship is carried out on lines even more lavish than those usually accorded to a modern first class liner. In fact, although only 22,500 tons and carrying 730 passengers, a total load of 450 kW is used for lighting alone. The illumination of the public rooms (see figs. 17 to 27 inclusive) is effected by three main methods: (1) concealed lighting in opaque cornices, (2) diffused lighting through continuous glazed cornices, (3) boxed laylights glazed with tinted diffusing glasses in modern designs.

Fig. 20.—The main lighting of the library is by indirect means from a concealed cornice reflector.

The first class dining saloon, to which the architect has imparted an Eastern atmosphere, has a well opening, which gives an increased height in the centre of the room (fig. 17). Above the opening is an illuminated ceiling, comprising a series of eight laylights, the metalwork of each of which is finished in black lacquer, and glazed with tinted glass panels of delicate shades of yellow, green and white. An illuminated glazed cornice surrounds the well opening, and is generally of a pale yellow colour with a decorative feature, glazed with green and red panels interposed at intervals. Additional light is provided by glazed columns at the four corners above the well. The lower level ceiling is mainly lighted by indirect means from mirror reflectors concealed in the cornices, while shallow laylight type fittings are fitted fore and aft. These are treated in a similar manner to the main laylights and glazed cornice. At the outboard are a series of boxed ceiling fittings, characteristic of the whole of the fittings in this room. The windows, both on the port and starboard, are floodlighted behind decorative glazed grilles.

The whole of this saloon is beautifully and

Fig. 21.—Main central fitting in the library.

adequately lighted, with a complete absence of harshness or glare, by approximately 1,800 Osram lamps.

Leading to the saloon is the foyer, which is treated in a similar colour scheme of lighting, with shallow laylights of similar character to those in the saloon.

The first class lounge (fig. 18), is another delightfully attractive room, which obtains its main source of illumination for the central area from the indirect

cornice lighting immediately below a large glazed and floodlighted laylight ceiling. The gallery surrounding the lounge has a number of decorative laylight type fittings spaced around the ceiling, and are of brushed silver finished metalwork, and glazed with a delicate pink flashed glass. Opening off this bays, is fitted with a glazed decorative cornice which surrounds each bay, and here again a combination of brushed silver metalwork and pink flashed glass affords a restful but efficient lighting source. Four beautifully designed and decorative standards of brushed silver with black relief are fitted at the

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Fig. 22.—Dancing space, the lighting of which is of a particularly novel character.

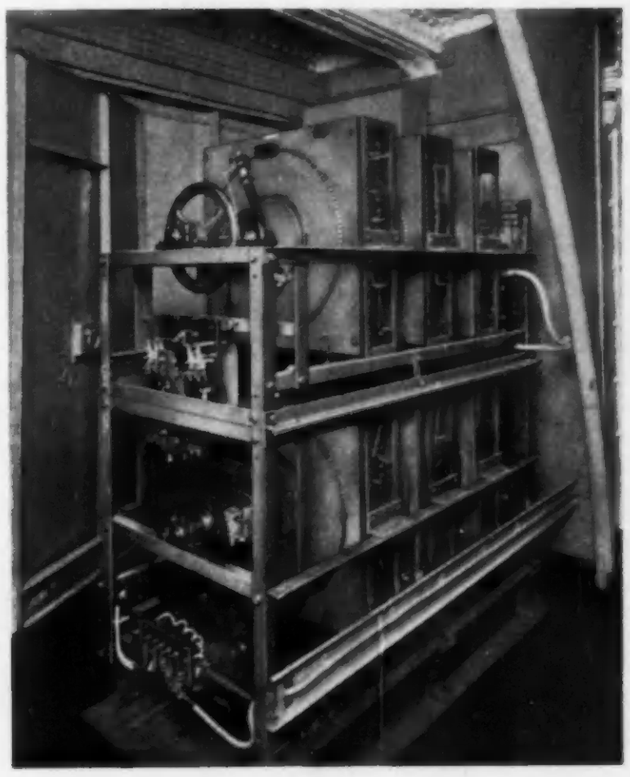

Fig. 23.—Dimmer controlling ~~three colour~~ lighting in ~~dance hall space~~ lounge

gallery are the verandahs, which are also lighted with similar fittings, though in this case the metalwork is finished a soft green. At the lower level of the lounge the ceiling, which is divided into recessed

fore and aft ends of this room, and are glazed with pink glassware (fig. 19). As the lounge, in which over 1,200 Osram lamps are used, is employed on occasions for showing talking pictures, and has a stage fully equipped with lighting for plays and concerts, the whole of the lighting is controlled by an electrically operated dimmer (fig. 23).

The library (fig. 20) is a particularly beautiful room, in which the main lighting is by indirect means from a concealed cornice reflector, though the addition of a main central fitting (fig. 21) and a small number of laylight type ceiling fittings in gilt colour metalwork and flashed pink glass provide the correct amount of semi-indirect lighting necessary for such a space. A feature of the library is the floodlighting of two niches.

The smoke room is remarkable for its decorative upper ceiling, and is fitted with two lanterns (fig. 25), which are outstanding examples of design and craftsmanship in electric fittings. These are finished in silver, with amber cathedral glassware, while enamelled ceiling fittings to match are employed, together with indirect cornice lighting, for the outboard wings of the room.

The dancing space (fig. 22) has a particularly interesting system of illumination. Three colour lighting is used for the main ceiling, and is controlled by dimmers (fig. 23) to give fading effects while dancing is in progress. These dimmers deserve special reference, as they embody a unique system of dimming developed for this purpose and patented by the G.E.C.

In this particular installation it was decided to discard, as being unsatisfactory, the usual scheme of dimming by means of series resistances in each circuit. This method is wasteful of energy, liable to the trouble of burning contacts, and concentrates a considerable amount of heat in the dimming resistances, which usually have to be stowed away in some small compartment, where the heat generated is a serious problem. Unless a very large number of contacts are used, the dimming consists of a series of jumps, giving an unpleasant effect. In the new system, the lights are dimmed through the medium of a negative booster, the voltage of which is controlled smoothly between absolute zero booster volts to full booster volts, which is equal and opposite to the ship supply.

Fig. 24.—One of the two verandah cafes, lighted by glazed cornices.

10155-30

Fig. 25.—One of the lanterns in the smoke room.

10155-39

For this purpose a motor driven regulator is provided, to which is also coupled a drum controller, arranged to connect each bank of lamps either direct to the line or to the booster, this change-over being carried out only at zero booster volts.

Special compensating fields and diverter resistances ensure that the change-over is carried out without producing the slightest flicker in the lamps. The booster voltage is then increased in opposition to the supply voltage, by the motor driven regulator, thus reducing the intensity of light gradually until the particular bank of lamps is extinguished. At this point the booster is changed over to the next bank of lamps in the sequence which is already extinguished and the booster volts gradually reduced.

The second bank of lamps is then gradually brought up to full brilliance, and is transferred to direct connection on the line, the booster transferred to the third bank of lamps and the whole sequence repeated.

Thus with three banks of lamps of, say, red, blue and green, one bank would be at full brilliance, one bank extinguished and the third bank would be varying from full brilliance to dim. The result is a pleasing and harmoniously gradual change of colour, which never deteriorates in quality, as only two of the three colours are in active use simultaneously.

Means are provided for amplifying the number of colour combinations available by leaving any or all of the individual colours permanently connected to the line, or alternatively disconnected.

By means of multiway switches it is also possible to vary the sequence of colour changes. Further, the lights may be used by direct switching without dimming when the booster is not in service.

After the booster has been started to work, the control of colour combinations can be effected through the medium of tumbler switches on the bandstand, which control the operation of contactors in conjunction with the motor driven controller.

With this scheme a surprisingly large variation of colour combinations can be effected, the exquisite effects of which must be seen to be thoroughly appreciated.

Decorative columns and wall panels in the dancing space, together with glazed cornices on the outboard ceilings, supply an adequate amount of lighting during such time as the colour lighting is not in use.

Fig. 26.—Swimming pool : under-water lights give a pleasing effect.

Two verandah cafes (fig. 24), fore and aft of the dancing space, are lighted by glazed cornices, and as these cafes are of a distinctly oriental character, the metalwork of the cornice is lacquered a Chinese red, with glazed bent panels of soft yellow, relieved with bright lines.

The swimming pool (fig. 26), gymnasium, cocktail bars (fig. 27), and the second class public rooms, are all equipped with specially designed fittings, some of the laylight type, others of glazed cornices, but the whole of the lighting furnishes an instance of the most modern and effective methods suitable for such luxurious standards as that of the *Queen of Bermuda*.

LIFTS.

The electric passenger lifts, one of which is shown in fig. 28, are in keeping with the high class decorative scheme chosen for the ship. Including service lifts, there are altogether eleven lifts in the boat, all of which were supplied and installed by the Express Lift Co., Ltd. (a subsidiary Company of the G.E.C.).

There are three geared variable voltage passenger lifts, each capable of raising a load of 1,500 lb. at 150 ft. per min. Variable voltage control is used on the latest type of high speed lifts and ensures absolutely uniform acceleration and retardation, thus avoiding discomfort to passengers, and also reducing the periods of acceleration and retardation to a minimum, giving the maximum benefits of high speed travel. These lifts are fitted with self-closing manually operated doors ; one lift serves nine decks and the other two serve seven decks.

There are also four direct coupled goods lifts, one of which can raise loads of 1,120 lb., one 1,680 lb. and two 3,360 lb. at speeds of 95 ft. per min. The first two lifts serve three decks and the others two decks.

In addition, four service lifts are installed. Each can raise a load of 560 lb. at 100 ft. per min. These lifts serve three, four and five decks.

GALLEY EQUIPMENT.

The G.E.C. electrical cooking and heating equipment installed in the Q.T.E.V. *Queen of Bermuda* is unique in the true sense of the word. Some idea of the extent of this portion of the electrical equipment of the vessel may be gathered from the fact that the maximum load which may be required for cooking is 620 kW.

Fig. 27.—First-class cocktail bar.

The equipment is installed in the main galley and pantries, bakery and confectionery shops, deck

service pantries, 1st and 2nd class dining saloons, crew's galley and hairdresser's, and comprises the following :—

2—8-oven island ranges.

Fig. 28.—"Express" electric passenger lift.

3—12′ combined hotpresses and carving tables.
1—9′ 6″ ditto
1—8′ 6″ ditto
2—7′ ditto
3—5′ ditto
1—5′ hotpress with bain marie top for soup service.
2—2′ 9″ hotpresses with bain marie top for soup service.
1—4′ hotpress.
1—4-compartment griller with hot cupboard.
1—3-pan fish fryer with hot cupboard.
1—2-deck pastry oven.
1—2-deck confectioner's oven.
1—confectioner's range.
4—salamanders.
3—hotplates, each 22″×20″.
1—20-gallon boiler.
Automatic toasters.
Waffle irons.

Island Oven Ranges.

Each of the two island ranges, fig. 29, consists of eight ovens, each 26″ wide by 28″ deep by 19″ high, having a maximum loading of 5.4 kW per oven. The heating elements are mounted at the sides and bottom, and are of the tubular pattern, totally enclosed, and are thus entirely protected. All connections are brought to the front of the range in wiring chambers which are also totally enclosed, and access to the elements is obtained by removing the wiring chamber covers. Monel metal is employed for hygienic reasons in the construction of the oven interiors, grids, pans and browning shelves, while the main structure of the range is built up from $\frac{3}{16}$″ and $\frac{1}{4}$″ mild steel plate, the doors being of cast iron. Asbestos lagging, 2″ thick, is used to confine

Fig. 29.—View in the galley showing two of the island electric oven ranges.

the heat to the oven interiors. A total of forty Magnet 12″ by 8″ embedded type hotplates are arranged in groups of four on each of the hobs.

An interesting feature of these ranges lies in the fact that the loading and method of mounting the hotplates is such that, while adequate heat is available for boiling and frying, undue overheating and the probability of consequent premature failure of the elements are eliminated.

All the oven connections referred to are carried to each end of the range and thence through trunking to the two control boards mounted on the canopy above in the form of stiff bare busbars, thus leaving the hob free of all obstructions.

Hotpresses, etc.

The general construction of all the hotpresses is similar. The tops are made of monel metal and the body of 14 S.W.G. steel plate. Tubular elements are provided for the bottom heat and also for the top heat. This system is standard to all hot cupboards and ranges.

All hotpresses in the main galley bay are fitted with carving dishes and sauce tureens on the top, whilst the interiors on the kitchen side are divided into sections to take the various sizes of dishes, whilst on the serving side of each hotpress the interiors are divided into sections for taking the various sizes of plates used. In this way each carver is provided with accommodation in the cupboard for dishes for his own need. Each carving dish is fitted with a cover having a sliding lid, which can be closed at will, fig. 30.

In all cases, the elements are arranged for 3-heat control, and the necessary switches, fuses and pilot

1095-15

Fig. 31.—Grill kitchen showing grill and hotcupboard.

lights are mounted on a separate board from the deck-head immediately above each respective cupboard.

10153-14

Fig. 30.—Electric hotpresses in main galley, fitted with carving dishes and sauce tureens.

Fish Fryer.

The fish fryer comprises three pans, each fitted with a folding lid. The pans measure 24″ × 16″ × 8″ and are fitted with a draining tap. Above the pans is mounted a canopy having a white vitreous enamelled lining and carrying a draining rack. The body of the fryer surrounding the pans is adequately lagged, while a heated hot cupboard space is constructed on similar lines to the hotpresses. Here, again, the requisite switches, fuses and pilot lights are mounted on a switchboard on the bulkhead.

Griller.

The griller, fig. 31, has four grilling chambers, each 20″ × 16″. The element coils are carried on panels at the top of the chamber and are protected by a suitable guard. For replacement purposes it is only necessary to lift up the top plate covering the four grilling chambers and take out the defective panel. Each chamber is lined with monel metal and is fitted with a rise and fall attachment, which can be fixed in numerous positions. A fat drawer is fitted below to retain the fats which accumulate during grilling.

A 20-gallon water boiler is provided, and this is mounted at the after end of the main galley bay. It is constructed with a copper interior, tinned inside, and steel exterior, whilst between the inner and outer casings, 2″ of cork lagging is introduced. Heat is obtained from two 4 kW blade type immersion heaters inserted through the side.

Salamanders.

The four salamanders are designed on similar lines to the 4-compartment griller. The interiors are fitted with a rise and fall attachment and are lined with monel metal, while the heating coils are carried on porcelain panels in the top and are protected by a guard. Access to the elements is obtained by raising the top of the salamander. Each salamander is arranged for single heat and is controlled by two separate "on and off" switches.

Fig. 32.—Electric baking and confectioner's ovens.

Hotplates.

Hotplates are installed for the purpose of making griddle cakes and scone cakes, and for this purpose even heating is essential. Each plate is constructed with a cast iron top and has a substantial wrought iron body. The coils are carried on porcelain formers immediately below the top plate, and on "high," "medium" or "low" the heating is uniform over the whole of the surface.

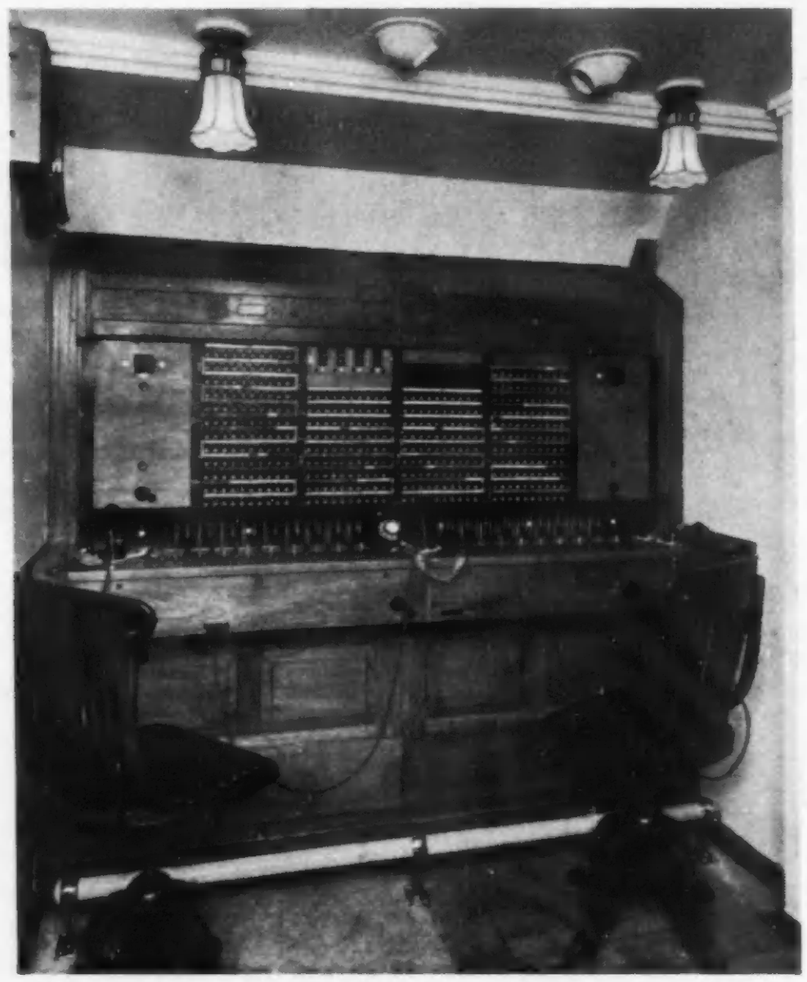

Fig. 33.—430-line central battery telephone switchboard.

Oven Room.

In here the baking oven, pastry oven and confectioner's range are installed (see fig. 32). The baker's and pastry oven are of the double-deck pattern, and are constructed along standard marine lines, having fire brick soles 4ft. wide by 5ft. deep. The tubular heating elements can be replaced without having to open the oven doors.

Warming Plates for Dumb Waiters in Dining Saloons.

A total of 39 plates are installed at various points in the first and second class dining saloons for the purpose of serving hot food direct to the passengers—the total loading of these plates being 10 kW. All these appliances are alike in their construction, the top of each hotplate being of polished steel and the body of polished brass.

Fig. 34.—Fire alarm system installed on bridge.

Standard Magnet strip elements are clamped on the underside, the maximum loading of the plates varying according to their size. One standard wattage element, however, is used throughout.

DECK SERVICE PANTRIES.

The deck service pantries are equipped with :—
3—2′ 6″ deck mounted hot cupboards.
2—3′ ditto
9—Bulkhead mounted hot cupboards.
Automatic toasters.

The hot cupboards are all double cased, the heating elements being of the tubular pattern, withdrawable from the front—rated at 1.75 kW for the deck mounted cupboards and 750 watts for the bulkhead mounted cupboards.

TOWEL RAIL HEATERS.

In a number of "de luxe" cabin suites there are fitted electrically heated towel rails finished in fescolised chromium plate, each having a loading of 50 watts.

COMMUNICATIONS AND SIGNALLING.

The various ways in which electricity is used for communication and signalling purposes on the vessel are full of interest.

A 430-line central battery telephone switchboard, fig. 33, together with a hand combination telephone in every cabin, provide ready communication between passengers and stewards.

A Magnet fire alarm indicator system is also installed. It is naturally of the utmost importance that, in case of fire, means of giving the alarm should be as perfect as humanly possible. A number of glass fronted alarms are placed in selected positions in the ship which, when operated, cause a luminous indicator situated on the bridge to warn the officer on watch, who is also afforded an indication as to the origin of the warning. The lines connecting the various alarm signals to the bridge (fig. 34) can also be used for telephonic communication by the simple operation of plugging in a hand telephone.

* * * *

While this description can obviously give but the barest account of the many unique features of the electrical equipment of this vessel, it is a matter of more than ordinary interest that one Company has supplied the whole of this equipment, every item of electrical apparatus recorded in this description having been made in one or other of the Works of The General Electric Co., Ltd., of England.

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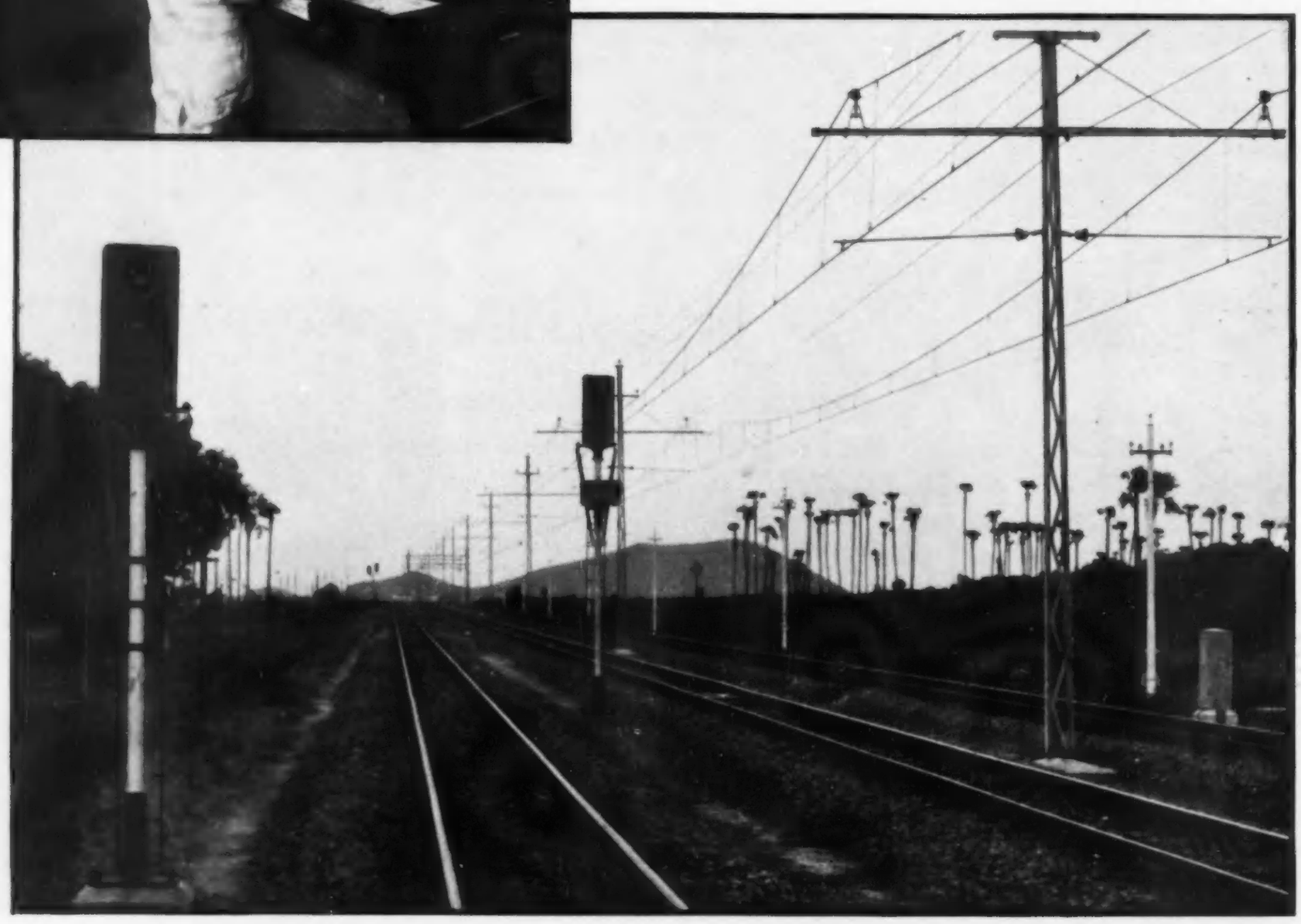
A Notable Installation on the South Indian Railway

(MADRAS SUBURBAN ELECTRIFICATION)

Power interlocking frame and relay cabinet at Pallavaram Station.

THREE-ASPECT COLOUR LIGHT SIGNALS ON 18 MILES OF ELECTRIFIED TRACK.

195 Alternating current track circuits extending over 41 track miles.
111 Power interlocking levers.
318 Light signals.
81 Power operated points.
243 Impedance bonds.
876 Relays.
35 Level crossings, automatically warned.
2 Level crossings with power operated gates.
400 Core miles of cabling.
Etc., Etc.

Made Entirely in England.

View of line approaching Tambaram (single steam line to Trichinopoly on left)